TOWER & SIEGMUND

The Design, Construction and Test of a Direct Reading Engine Indicator

Electrical Engineering

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THE DESIGN CONSTRUCTION AND TEST OF A DIRECT READING ENGINE INDICATOR

BY

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AND

HUMPHREYS OLIVER SIEGMUND

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1917

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May 31, 1917

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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Ira W Fisk
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The Design, Construction and Test of a Direct Reading Indicator.

I. Introductory.

The engine indicator is used in most engine tests to determine the force of a working medium acting on a unit area of the piston. Thus, knowing the area of the piston, the length of the stroke, the speed of the engine, and the pressure per unit area, termed mean effective pressure, the indicated horse-power can readily be obtained. Mean effective pressure is the average of the instantaneous pressures over the compression stroke. The ordinary indicator draws on a card the various changes in pressure in the cylinder during both the forward and return strokes of the engine piston. The instrument is made so that the ordinates on the card are proportional to the instantaneous pressures and the abscissae are proportional to the position of the piston in the engine cylinder. The area of the card is then proportional to the work done during one stroke, and knowing that work is the product of force times distance, the mean ordinate of the card, which is the area divided by the length, is proportional to the average force or mean effective pressure during the cycle.

At best the engine indicator is somewhat cumbersome to handle and involves the use of a planimeter to interpret the results. Moreover, the accuracy of the instrument is seriously impaired by the inertia of the moving pencil and multiplying devices practically limiting its use to engines whose speeds are below 400 revolutions

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per minute.

II. A Direct Reading Indicator.

In realization of the usefulness of a direct-reading indicator an investigation was conducted in which the characteristic property of a galvanometer to read the average of the instantaneous values of current, was employed. The fundamental idea involved a mechanism in which changes in pressure could be made proportional to changes in current in a Wheatstone bridge and that by proper calibration the galvanometer would read directly the average current which corresponded to a certain average pressure. Figure 1 shows the scheme of connections as was first suggested.

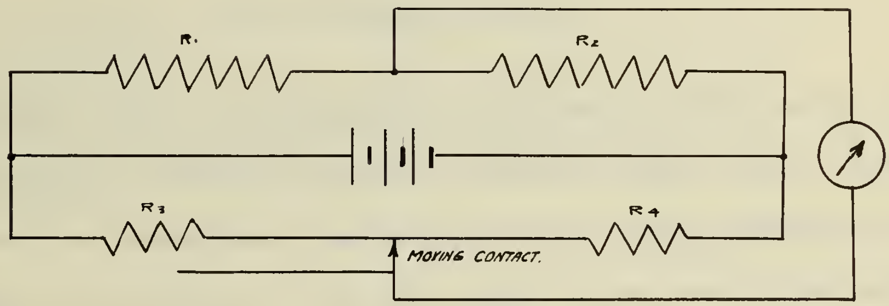

Fig. 1. Original Diagram of Connections.

The objections to this first scheme were numerous and it was almost immediately discarded because the variability of the resistances of the bridge continually destroyed the balance of the galvanometer. Later, however, difficulties arose which would have rendered the Wheatstone bridge method practically useless. These will be discussed later in connection with back-pressures and adjustments to compensate for negative work.

A much simplified and more reliable arrangement was next tried wherein the galvanometer was made a part of a potentiometer circuit,

one terminal sliding on the bridge wire. Figure 2 shows the connections for this circuit.

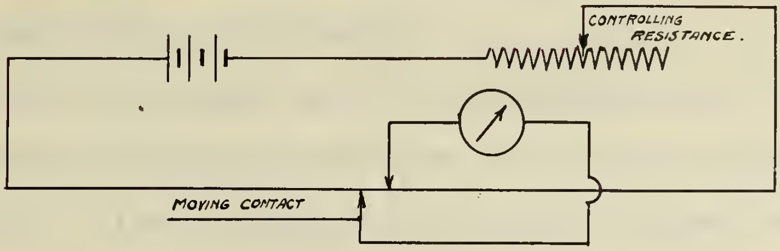

Fig. 2. Diagram of Revised Circuit.

In the preliminary investigations this circuit proved most satisfactory and all of the tests in connection with the selection of a suitable contact material and slider design were conducted from a set-up based on this potentiometer principle.

III. The Sliding Contact.

It was evident from the begining that one of the parts that would cause the most trouble was the contact which was to travel on the bridge wire, so extensive investigations were conducted on different types of sliders. For the sake of accuracy the slider had to be designed so that it would not add to the inertia of the instrument, yet be substantial enough to withstand high speeds; it had to make good contact with the bridge wire at all speeds, yet not wear the metal surface too rapidly.

For the purpose of developing a slider a machine was constructed shown in Figure 3 that would give the motion of an indicator piston. A one-fourth horse-power direct current shunt motor was used, with resistance in both armature and field circuits for speed control and speeds from zero to 4500 revolutions per minute were available. By means of a crank-pin on the shaft and a rod connecting the pin to a cross-head, the rotation of the armature was changed to the

reciprocating motion of the indicator. Fastened to the cross-head was another rod the ends of which extended over the bridge supports and carried the slider to be tested.

Two methods, one making use of the galvanometer, the other involving the oscillograph, were used to test the accuracy of the sliding contact. First, knowing that with a uniform rotational speed the contact described a simple harmonic motion over the bridge wire, it was evident that the variation of the current in the galvanometer circuit, Figure 2, followed a sine law. Unlike an ordinary alternating current wave, the variation of current was uni-directional since the galvanometer terminals changed in poten-

Fig. 3. Machine for Testing Sliding Contacts.

tial but not in polarity.

Let us assume a sine wave relation as shown in Figure 4. With reference to the zero line, the variation of current is expressed by the equation

$$i = I \sin \theta + I \qquad (1)$$

Now if the variable and fixed contacts are together no current will flow and the instrument will read zero. If, however, the movable and fixed contacts are at a maximum distance apart, maximum current

flows and the galvanometer reads a deflection, 2m. Knowing that in an aperiodic galvanometer, current is proportional to the resisting torque, which in turn, is proportional to the angle of deflection,

$$i = \frac{T\theta}{Bs} \tag{2}$$

where T is the resisting torque for one unit deflection, θ is the number of unit deflections, B is the flux density of the permanent field, and s is the effective area of the moving coil. When the

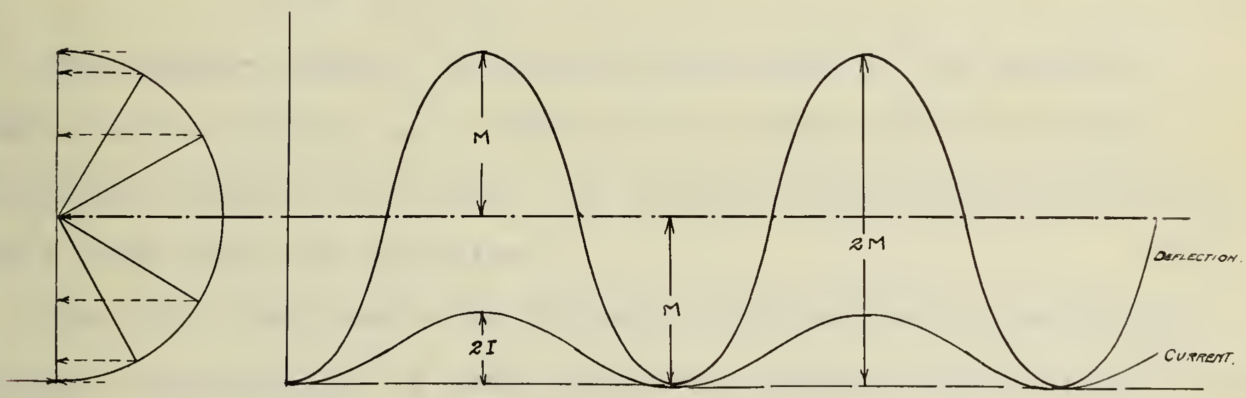

Fig. 4. Sine Wave from Simple Harmonic Motion.

current changes too rapidly for the moving element to follow, the coil takes up a position corresponding to the average of the instantaneous torques and consequently reads a value proportional to the average of the instantaneous currents. Therefore, without regard to the speed, when the slider moves in a harmonic motion, giving what is known to be a variation of current, as expressed in Equation 1, we would expect the reading of the instrument to be the average of the corresponding deflections which follow the same law,

$$d = m \sin\theta + m \tag{3}$$

Integrating this expression between the limits of 0 and 2π to find the average deflection,

$$\text{mean } d = \frac{1}{2\pi}\int_0^{2\pi}(m \sin\theta + m)\, d\theta \tag{4}$$

$$\text{mean } d = \frac{1}{2\pi}\Big[m \cos\theta + m\theta \Big]_0^{2\pi} \tag{5}$$

$$\text{mean } d = \frac{(m - m)}{2\pi} + \frac{2\pi m}{2\pi} \tag{6}$$

$$\text{mean } d = m \tag{7}$$

The average current is therefore one-half of the maximum instantaneous current as is shown by the fact that the average deflection should be one-half the maximum instantaneous deflection for a true sine law variation.

The first test proved to be quite satisfactory in selecting a suitable contact, but in cases where the contact will not follow the sine law requirements, this scheme did not afford any sound method of determining just where the trouble was. In order to find out what was happening during the travel of the slider over the wire, an oscillograph was used, and actual photographs of the instantaneous current variations were taken.

Here, again, the ideal case would follow the sine law of current variation and for a perfect contact, the record should show a pure sine wave. On the oscillograms, any variation in the contact resistance showed up plainly as a variation in the regularity on the sine curve. The actual records and photographs show how conspicuously these defects asserted themselves. In the investigations of all sliders and contacts both the galvanometer and oscillograph tests

were applied with results that will be discussed later.

The first contact that was tried took the form shown in Figure 5 and was just a rigid, wedge-shaped piece of brass fastened on the

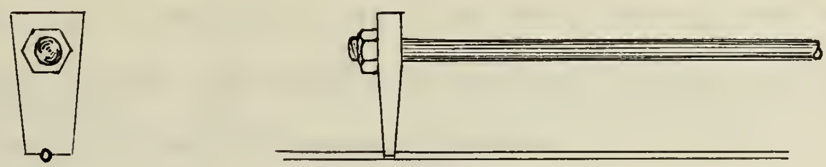

Fig. 5. Contact Number 1.

end of the rod. This was run at several speeds and it was almost immediately found that the wear between the contact and the bridge wire was too great because of the rigidity and this type was therefore out of the question.

The next slider that was made is shown in Figure 6, and consisted of a steel bob held in place in a vertical bearing by a spring which exerted a pressure on it at the top. This design left room for a

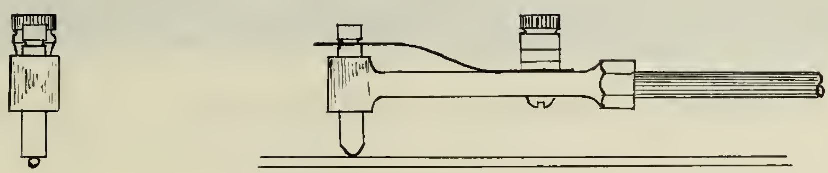

Fig. 6. Contact Number 2.

considerable amount of relative transverse motion between the slider and the bridge wire. Several tests were made on this contact at different speeds and it was found that at low speeds when the contact point and the bridge wire were both new, the contact was a fairly good one over the length of the stroke, but when the speed was

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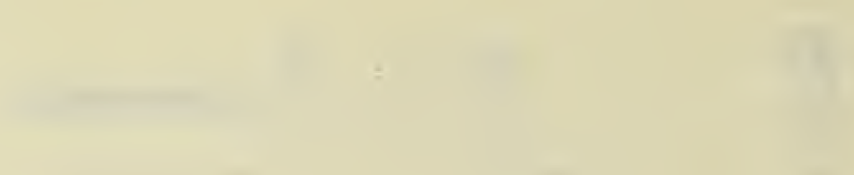

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increased the contact jumped off of the wire and wore it severely probably because of the slight inertia of the steel bob. Figure 7 shows the first oscillogram taken with this slider in use. It can readily be seen that the general shape of the curve traced out is a sine curve but the irregularities show that the slider was jumping sometimes clear off of the bridge wire even though the motor was running only at 400 revolutions per minute.

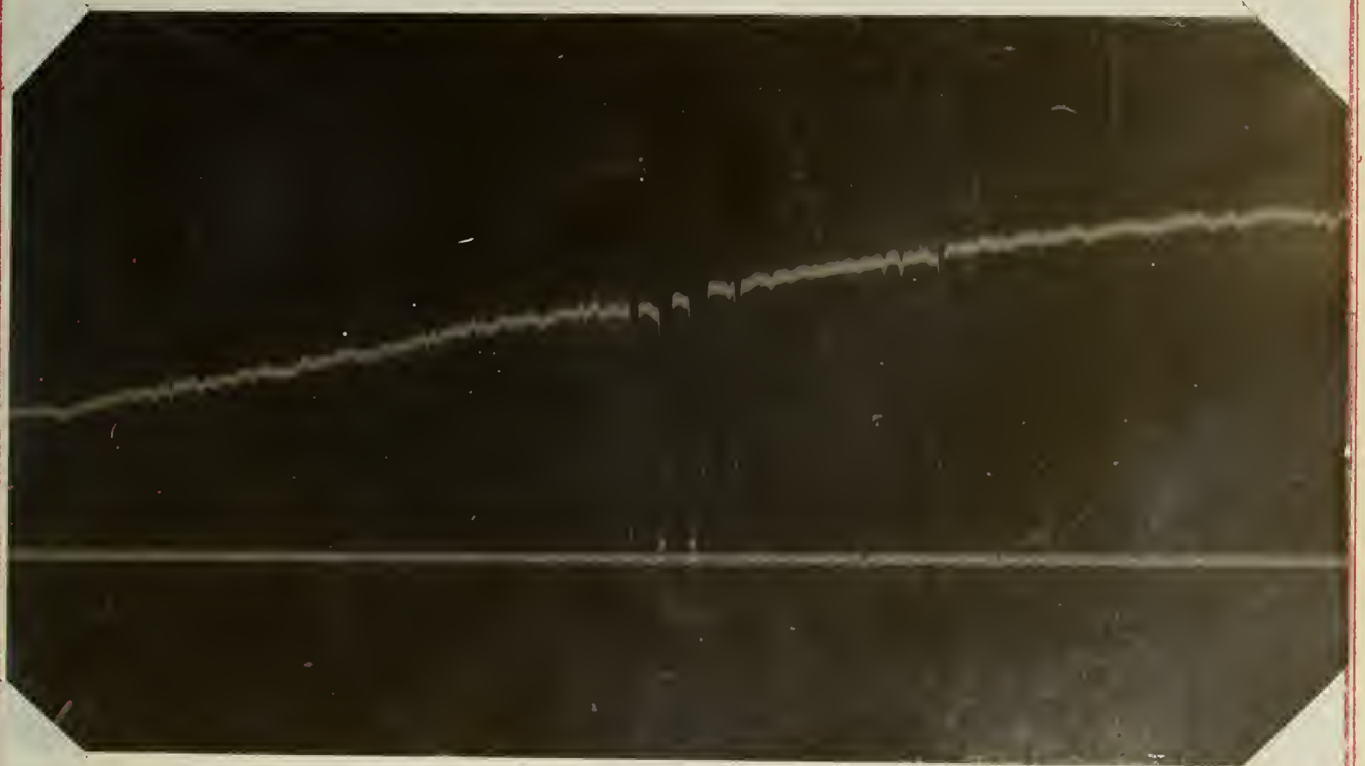


Fig. 7, Oscillogram of Contact 1, Speed 400 r.p.m.

Figure 8 shows the same slider when the speed was 800 revolutions per minute. The contactor was not staying on the wire as is indicated by the jags in the fundamental sine curve. The galvanometer tests likewise showed that with the increased speed there was a decrease in the readings showing that the contact was not perfect. Table 1 gives the results of a typical contact test.

Table 1.

Minimum	Maximum	Reading	Calculated Mean
60	312	176	186
70	346	194	208
70	347	198	208

Since the actual readings are less than the calculated sine wave

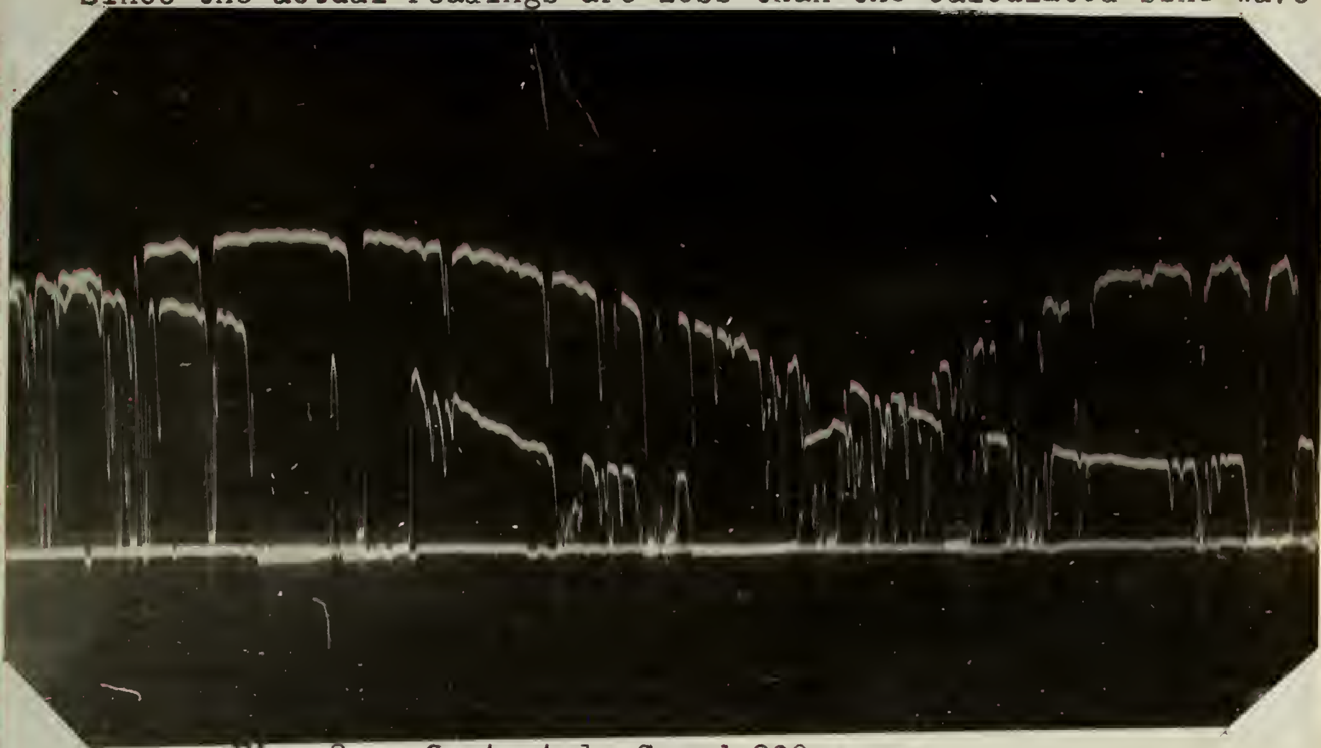


Fig. 8. Contact 1, Speed 800 r.p.m.

mean values it is further evidence that the contact was leaving the wire completely thus reducing the average of the current values. This same contact was tried using different metals for the contact face. Figure 9 shows a steel bob on a German-silver wire at a low speed, Figure 10 shows a brass bob on a German-silver wire at low speed, (below 400 r.p.m.) and Figures 11 and 12 show respectively the steel and brass bobs at 1200 and 1600 revolutions per minute. Both contacts caused a considerable wear on the wire at these higher speeds and the galvanometer tests were as low as two-thirds of the calculated theoretical mean. Though more successful than the first

Fig. 9. Contact 1, Steel Bob, German-silver Wire.

Speed Below 400 r.p.m.

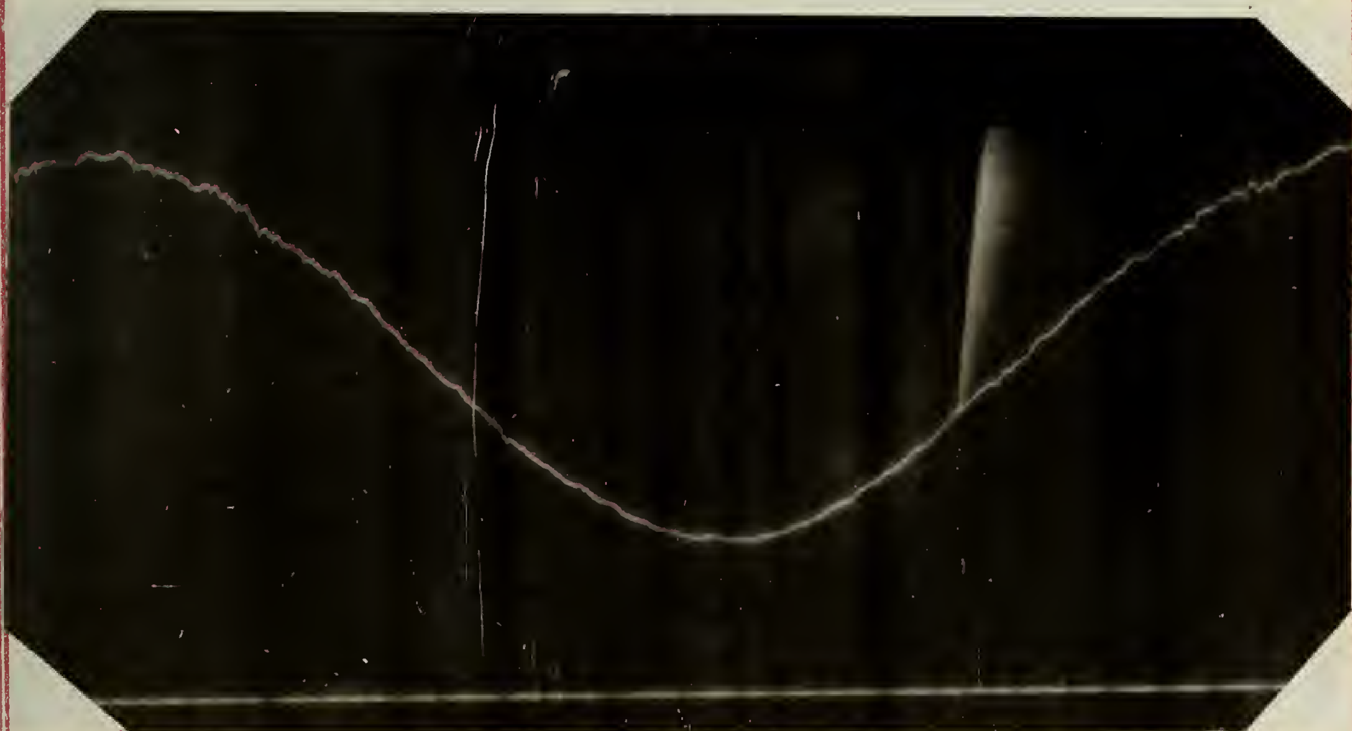


Fig. 10. Contact 1, Brass Bob, German-silver Wire.

Speed Below 400 r.p.m.

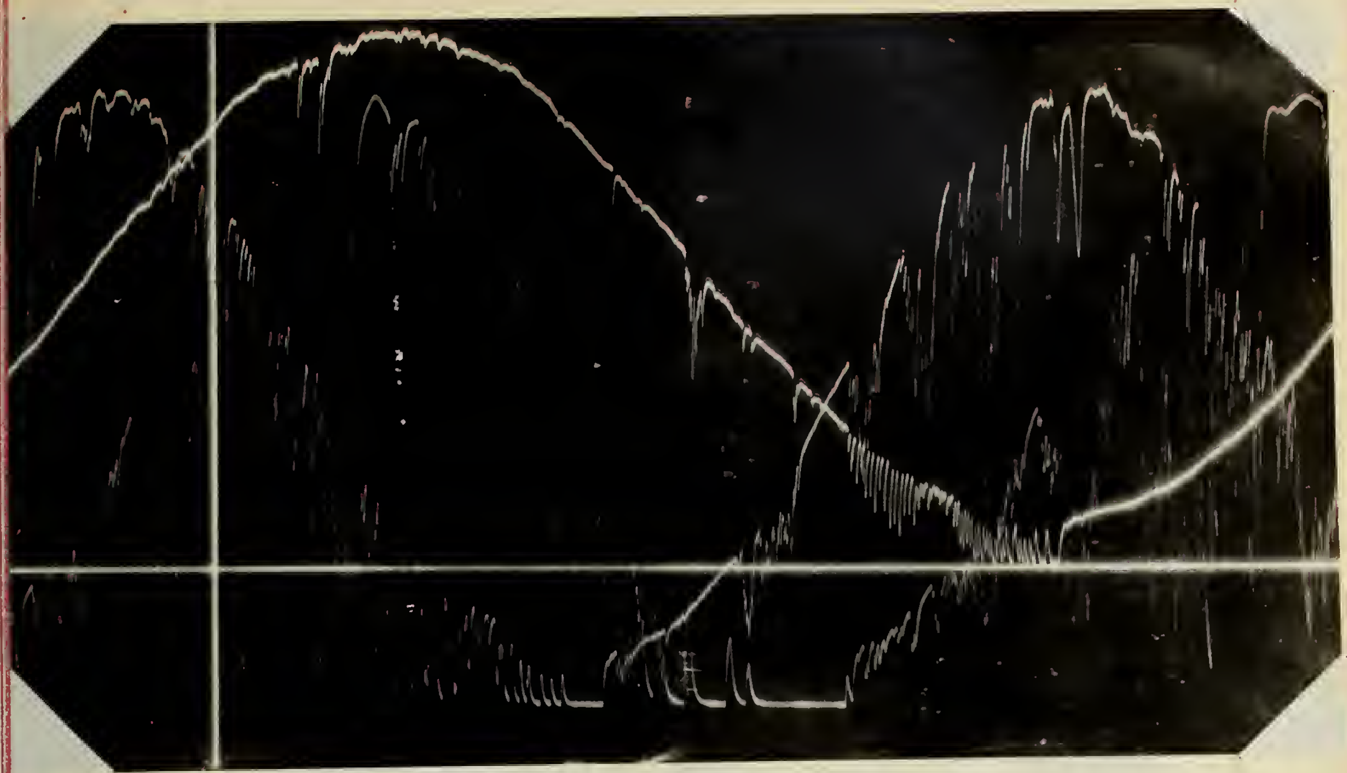


Fig. 11. Contact 1, Steel Bob, German-silver Wire.
Speed 1200 r.p.m.

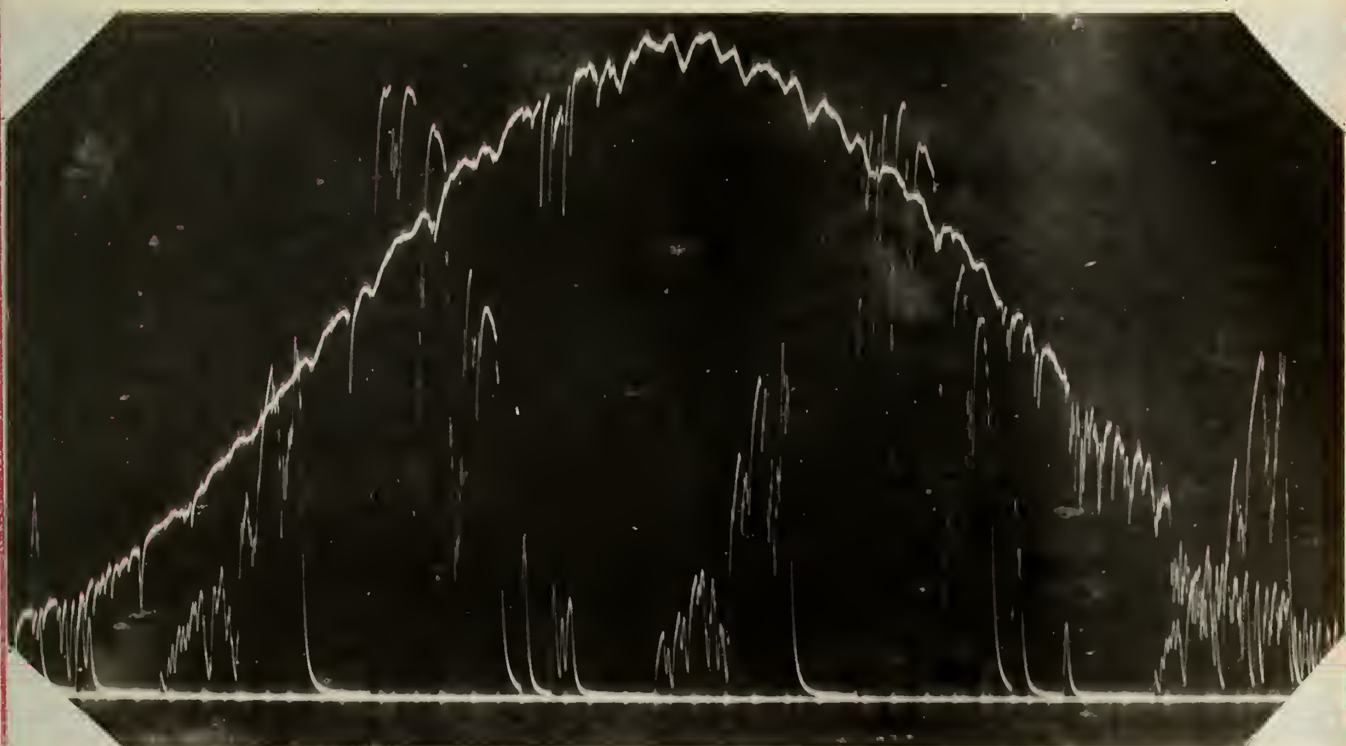


Fig. 12. Contact 1, Brass Bob, German-silver Wire.
Speed 1600 r.p.m.

type of contact, this spring bob scheme was discarded in favor of a more simple, and what proved to be a more satisfactory arrangement.

It might be said that various mercury contact devices were resorted to with little or no success, the most notable of which was a scheme in which the bridge wire played through a mercury bath, Figure 13. Although with this method an excellent contact was

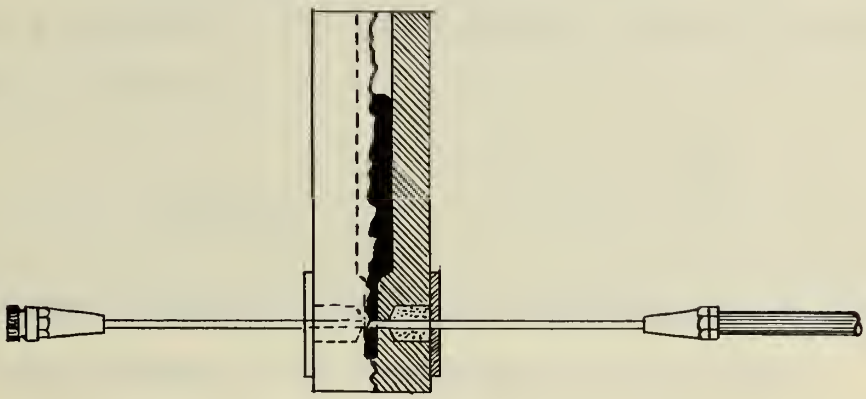
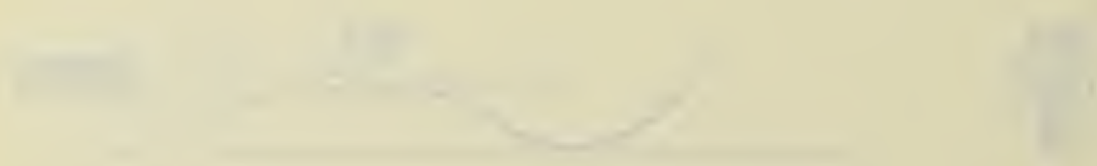


Fig. 13. A Typical Mercury Contact.

obtained, the friction at the stuffing boxes where the bridge wire entered the mercury was so great that the scheme was practically worthless.

Fig. 14. A Steel Spring Contact.

The contact that gave the best results consisted of a piece of spring steel bent into the shape of a letter S and fastened to a rigid support as shown in Figure 14. The first style of this



contact had both ends fastened to the supporting rod. Figures 15 and 16 show the records obtained from tests of this style of design at low and high speeds. The spring was then changed so that it was supported at one end only as shown, and a series of tests were made using a manganin wire for the bridge. Figure 17 shows the oscillograms of this contact at 600 and 1800 revolutions per minute. Figure 18 shows the same contact with minor improvements at 800 and 1800 revolutions per minute. The galvanometer test of the last contact is given in Table 2.

Table 2.

Data from Contact 3 Showing the Deflection of the Galvanometer to be Independent of the Speed.

R.P.M.	Current	Minimum	Maximum	Reading	Average	Calculated
152	0.15	0	13.8	6.80		
200	0.15	0	13.8	6.80		
328	0.15	0	13.8	6.80		
528	0.15	0	13.8	6.82		
852	0.15	0	13.7	7.00		
1556	0.15	0	13.7	6.80		
1932	0.15	0	13.7	6.80	6.83	6.88

Here it is noticed that the galvanometer reading remained practically constant at the theoretical mean over a high range of speed. This last fact coupled with the oscillograph records justified the adoption of the sliding spring contact and verified the theoretical mean reading of the galvanometer. In addition to this performance the contact when operating over a high range of speed with no current in the bridge wire showed no galvanometer deflection, proving that there were no thermo-couples to impair the accuracy of the readings.

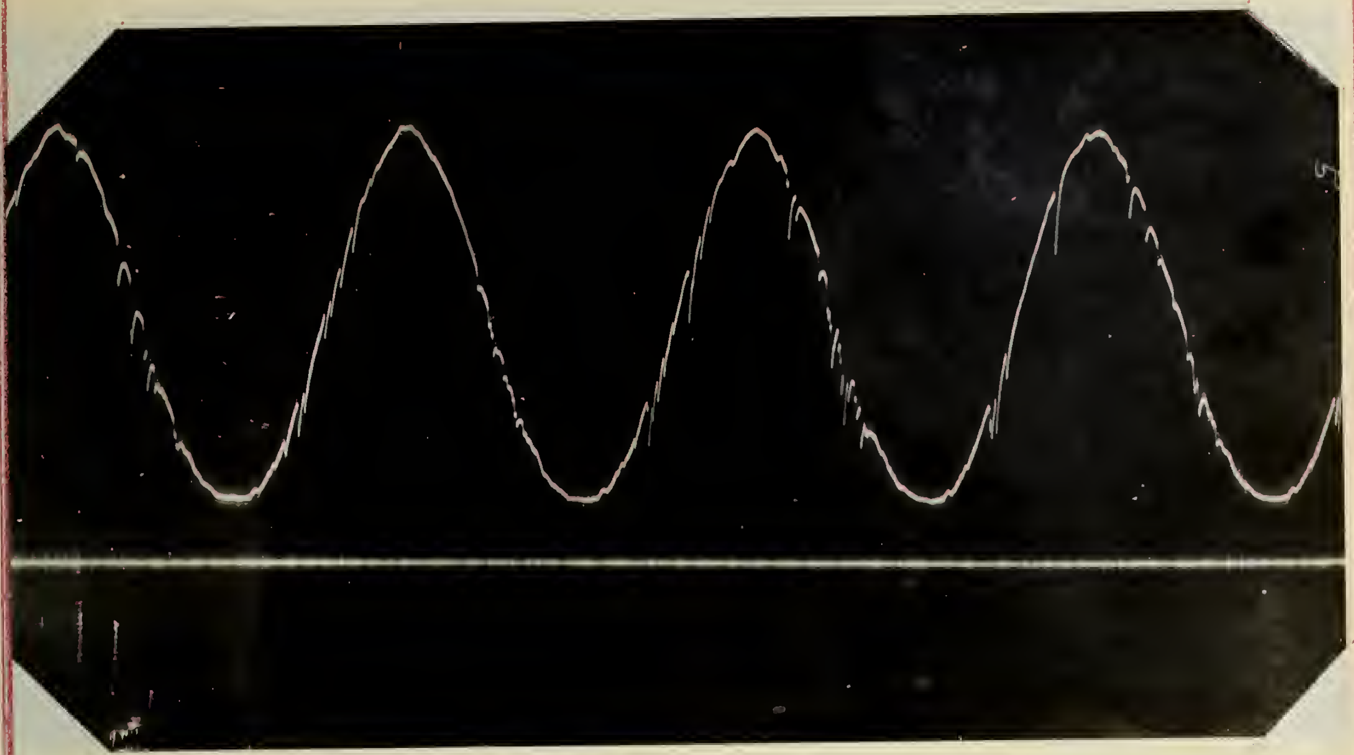


Fig. 15. First Record from Spring Contact.

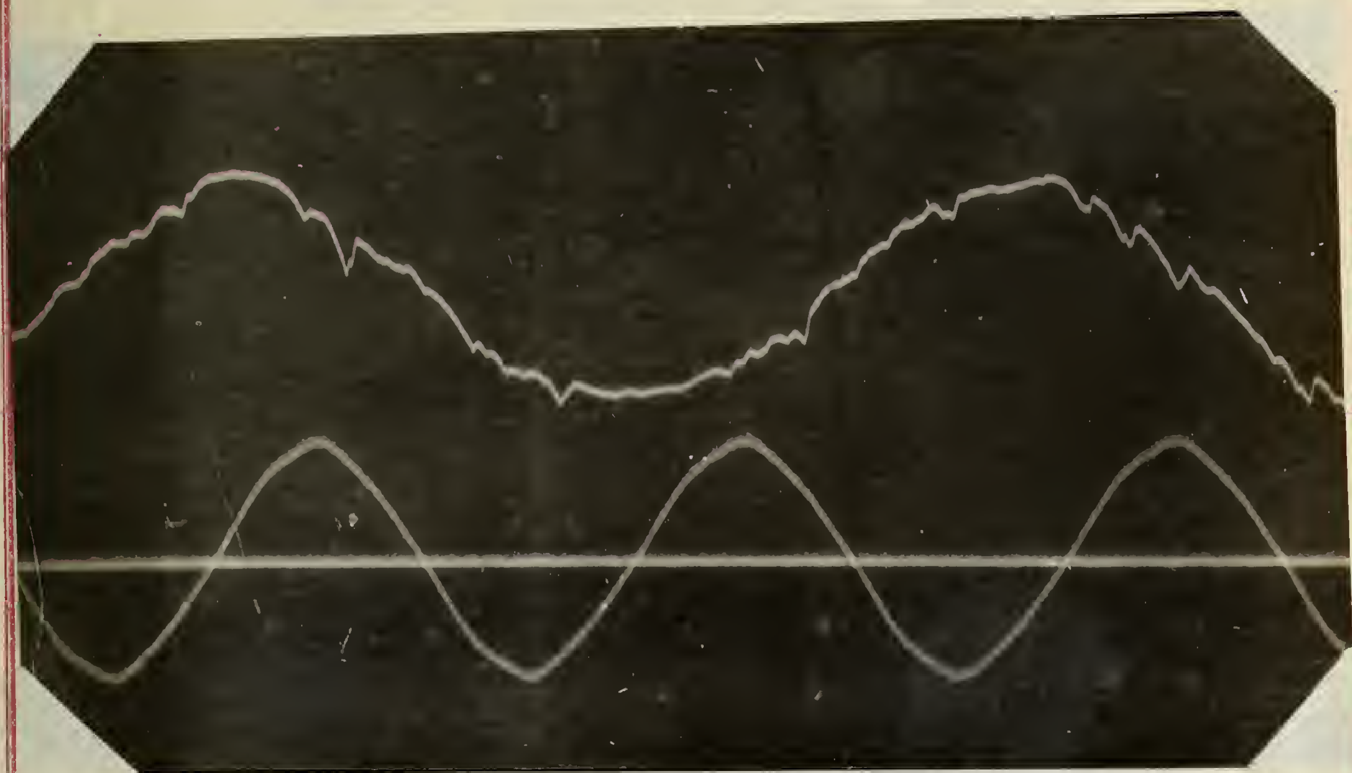


Fig. 16. Second Record from Spring Contact.

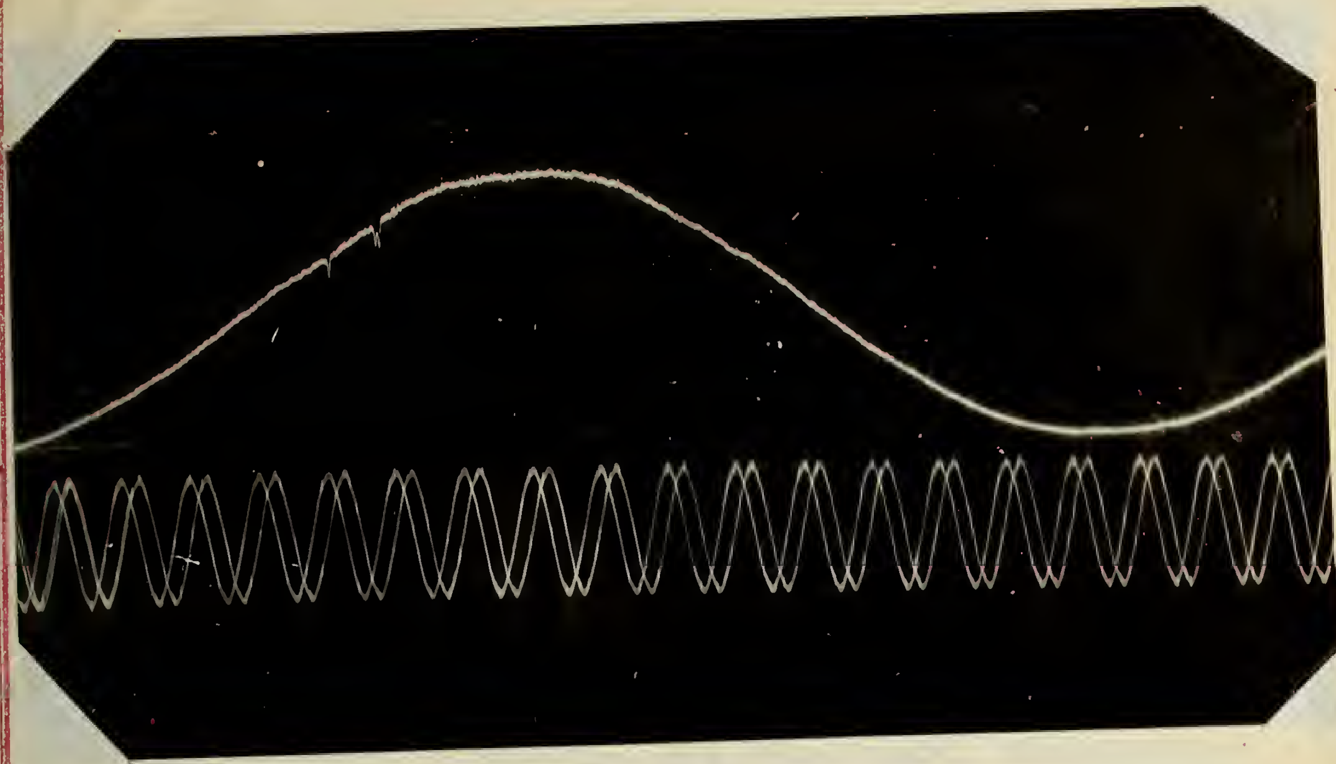


Fig. 17. Contact 3 at 600 and 1800 r.p.m.

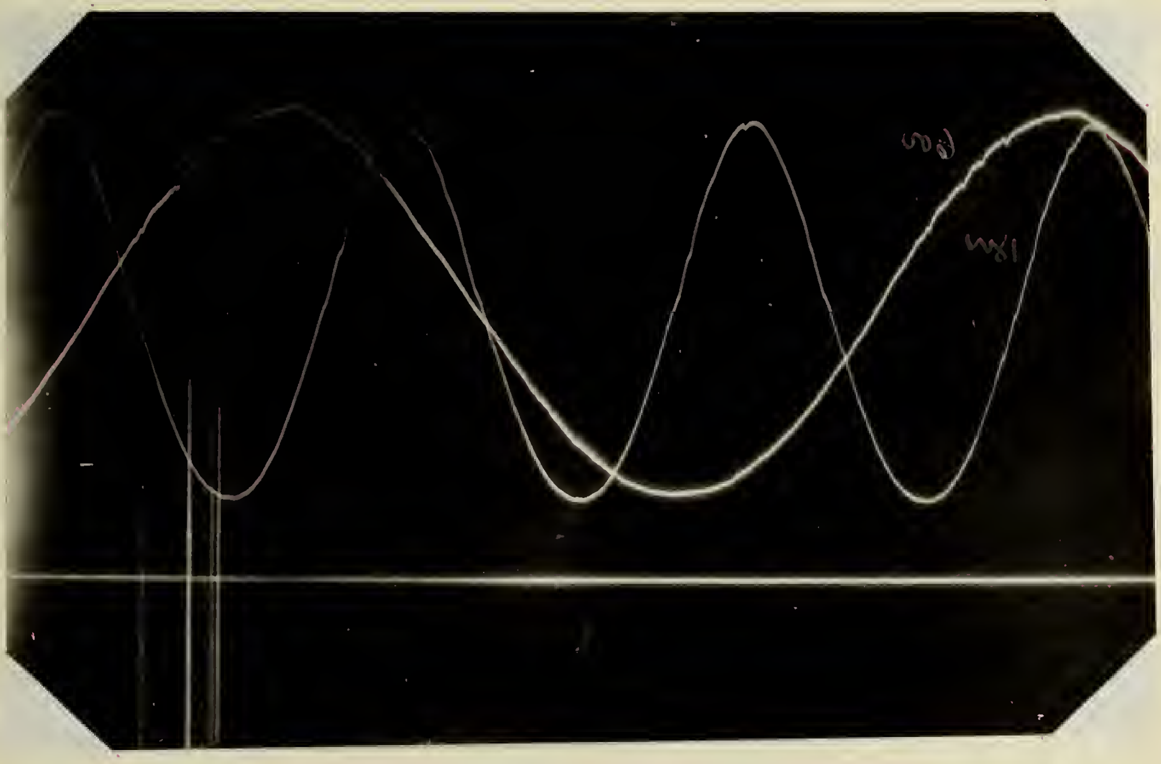


Fig. 18. Contact 3, Improved, at 800 and 1800 r.p.m

Neither did this design of slider wear the manganim bridge wire in spite of the fact that in the endurance test the contact was run for an abnormal length of time under the most severe conditions of speed. After a week of continual use in tests ranging in speed from 400 to 2000 revolutions per minute and lasting for at least two hours each day, there was not any apparent wear on either the bridge wire or the sliding contact.

IV. Bridge Wire Suspensions.

After a satisfactory slider was developed attention was turned to the method of holding the bridge wire in place. The first way tried was naturally to have the wire drawn tight, resting on a wooden base and fixed at both ends by metal clamps after the fashion of a Wheatstone bridge as used in a laboratory. While a bridge so constructed gave a certain amount of satisfaction when new, it was found that after a little use the wire was forced down into the wood by the pressure of the contact above it, with the result that points on the surface of the wire stood a different heights, presenting an uneven path to the slider. While at low speeds with the later forms of contacts this condition was not as objectionable as it was with the early contacts, it was practically the only thing that kept the contact from reading accurately at high speeds. It seemed that some type of freely suspended bridge wire should give still better satisfaction since if it were drawn quite tightly it would have a high period of vibration and would be able to keep in contact with the slider if it jumped up and down.

The first bridge in which the wire was suspended was made as shown in Figure 19. The two terminals were made very heavy so that

they would not be deflected by the tension in the wire, which was pulled tight by the thumb-screw at A. At first it was thought that a ball bearing should be placed at C so that when the screw A to which the wire was fastened, was turned, the whole wire would turn and relieve any torsional stresses that might be set up if C were

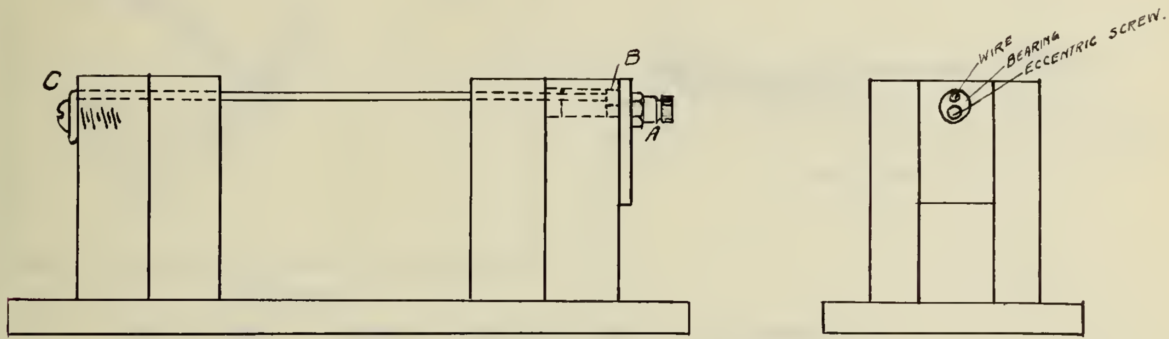


Fig. 19. Original Wire Suspension.

fixed. In the construction, however, it was decided to make the bearing at B eccentric so that it would not turn when the screw was taken up. That permitted the bearing at C to be fixed also.

Tests on this type of bridge showed that it was a step in the right direction but it was obviously too heavy for a finished machine. No difficulty was experienced in drawing the wire very tight and the slider seemed to follow it very well. It might be well to say here that all of the bridges were made so that from three to five inches of wire were free for contact so that the behavior of the slider could be observed over both long and short strokes.

Figure 20 shows the essentials of the next suspension scheme that was tried. One end of the wire was fastened by brass cleats at A while the other end was fastened to a grooved cylinder secured to the base eccentrically by a screw at B so that when the

lever C was turned around on its guide D, the wire would be put in tension. This bridge was not quite as satisfactory as the preceeding one because it was hard to keep the wire stretched, the fastening at A giving most of the trouble. Several tests were run on it,

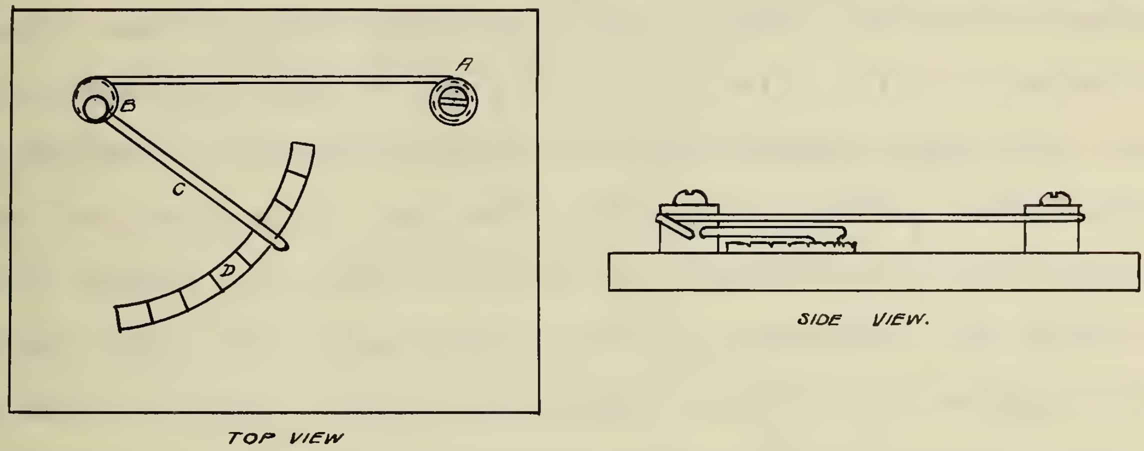


Fig. 20. Second Bridge Wire Suspension.

however, and it showed again that a wire which was supported at two points only, worked best.

The last type of suspended bridge tried is shown in Figure 21. In this case the wire was again closer to the wooden base but because it was supported between metal cleats, it did not rest on the base

Fig. 21. Third Method of Suspending Bridge Wire.

as in the first one.

By this time both suspension and sliding contact were well enough developed to permit the indicator itself to be constructed.

V. Design and Construction of the Indicator.

The direct-reading indicator was designed and built to fit any Crosby inside-spring engine indicator. Since the direct-reading device made use only of the piston and spring, all of the multiplying mechanism, reducing motion, and card-holding parts were removed from the instrument. The shaft holding the sliding contact was fixed rigidly on to the piston of the indicator and by a suitable support built on to the cylinder of the instrument, the bridge wire was held in place. Before describing further the details of the construction, it is well to consider some of the requirements of the machine.

In the first place, all of the parts had to be made rugged, yet as light as possible. The instrument in test is always subjected not only to the violent vibrations due to the explosions in the engine, but is also exposed to the excessive heat of the cylinder. It was therefore important that all of the parts be made as secure as possible, and that no materials be used that were brittle or were apt to be injured by the heat. As inertia is a source of great error in any indicator, too much care could not have been exercised in making the moving contact as light as possible nor in reducing the friction to a minimum. In as mush as there were two separate electric circuits on the indicator, and in view of the fact that the sliding contact is inherently grounded on the engine, it was necessary to observe the utmost precaution in assuring absolute insulation, since the slightest leakage would affect the galvanometer. In addition, it was essential that arrangements be made for replacing the spring inside the indicator, and for

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renewing the bridge wire.

Aside from the mere mechanical problems which presented themselves another difficulty arose concerning the back-pressure of the engine. In gas engines, and in steam engines particularly, the back-pressure is not always at atmosphere; in fact in compound engines, it is not uncommon to find one cylinder exhausting into 30 or 35 pounds pressure, while another may exhaust into 26 or 28 inches of vacuum. Obviously then since mean effective pressure is not dependent on exhaust pressure but on the difference between the mean power-stroke pressure, some scheme had to be devised to take care of the back-pressure into which the engine was exhausting.

For a solution of this problem, let us assume an indicator card as shown in Figure 22. The development of this card into a pressure-time diagram will take the form shown in Figure 23. The average of

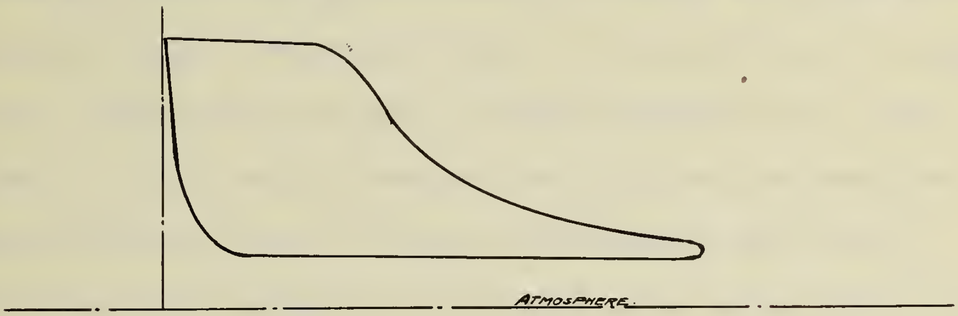

Fig. 22. Typical Steam Indicator Card.

the ordinates represented by the lines yy' will give the mean pressure above atmosphere. In the cylinder, however, we are not concerned with this average but with the mean pressure above the minimum cylinder pressure. The distance between the atmosphere line and yy' represents the mean pressure above air, and would correspond to the reading of the galvanometer if the instrument had been set to read zero at atmosphere. We are not interested in such an

indication, but are after the reading corresponding to the difference between the minimum pressure line xx' and the average line yy'.

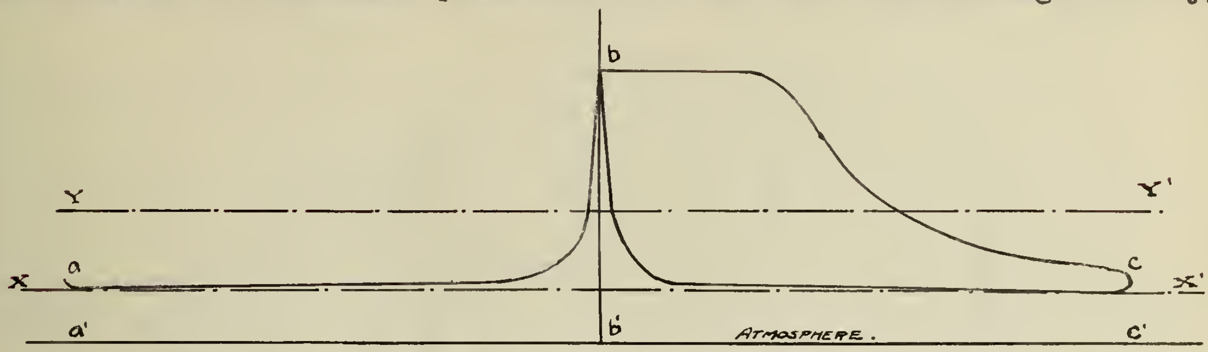

Fig. 23. Pressure-time Diagram from Figure 22.

The adjustment was obtained in the actual indicator by fastening the fixed contact of the potentiometer circuit on a micrometer screw which could be turned up and down, and calibrated so that for any back-pressure the galvanometer could be made to read zero. By this adjustment, the fixed galvanometer circuit terminal was set at a point on the bridge wire such that for the position of minimum pressure, the slider contact was directly opposite the fixed terminal. Thus no potential difference would exist between the two galvanometer terminals and it would accordingly read zero.

Another vital consideration was discovered along with the back-pressure adjustment, which was concerned with the subtraction of pressure on the compression stroke. This operation was secured by means of a commutator which is discussed in a later section dealing with negative work.

Figure 24 shows a photograph of the completed indicator and Figure 25 shows a detail of the construction. Referring to Figure 25, the cylinder, plunger, and spring are recognized as the standard equipment of the Crosby Instrument Company. The brass bed-plate A is fastened to the cylinder by a screw S and by a nut securing the

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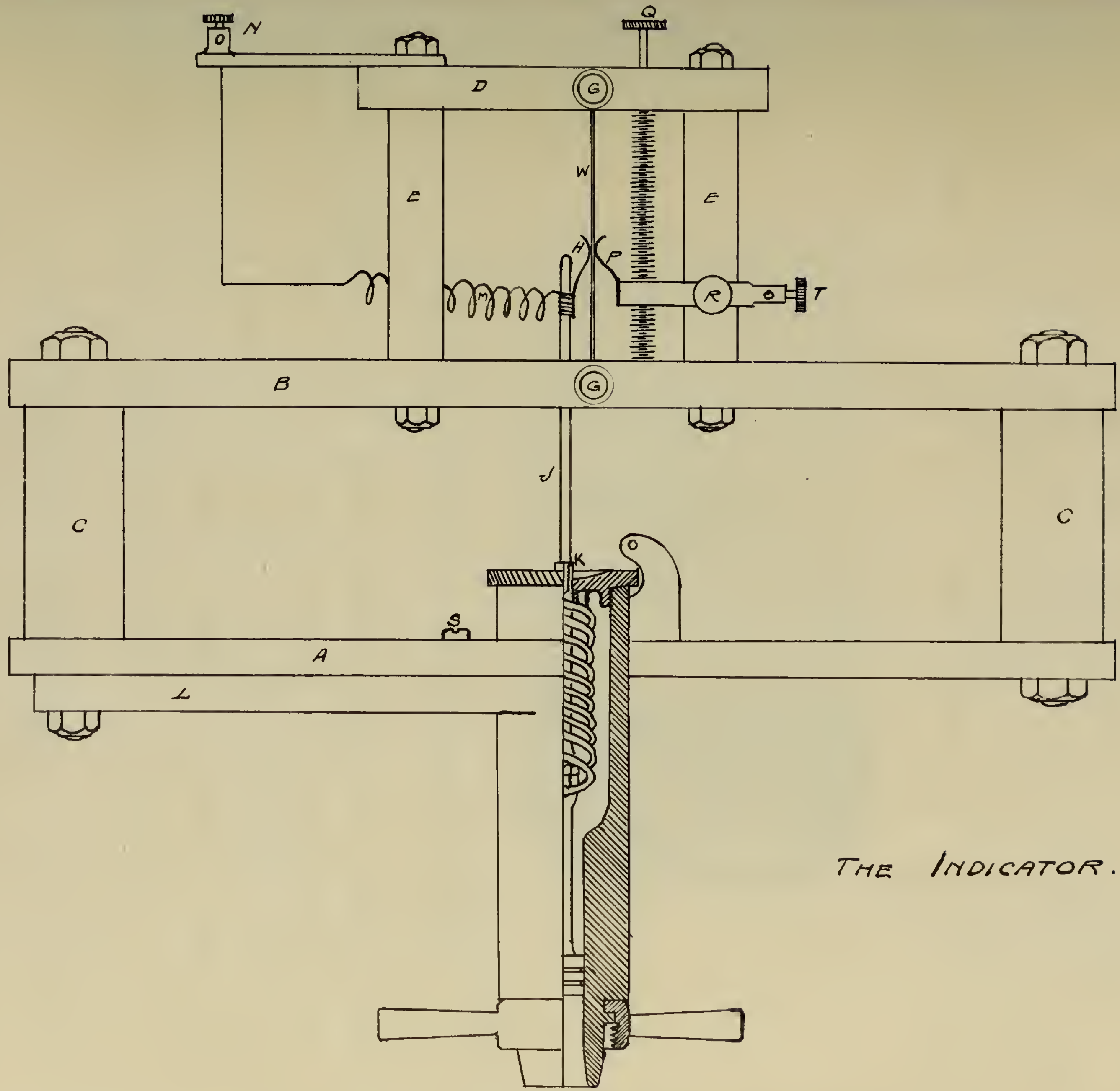

THE INDICATOR.

FIGURE 25.

pillar to the lip L which is a part of the original indicator. The fibre support B holding the bridge wire is held in place by the brass pillars C and is bolted down as shown. The other fibre bridge wire support D is held in place by smaller brass rods E. The bridge wire W is held in brass lugs that are tightened by set-screws G which also serve the purpose of terminals for the bridge wire circuit. The sliding contact H is made of watch-spring steel and is soldered to the aluminum rod J which is in turn screwed into the shaft of the

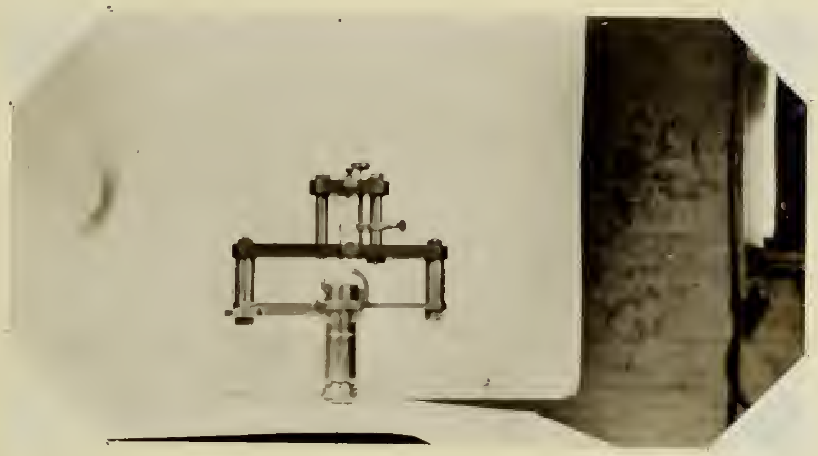

Fig. 24. Photograph of Completed Indicator.

indicator plunger at K. A copper helix connects the slider to the galvanometer terminal N. The fixed contact P is adjusted by the micrometer screw Q and is held fast in place by another thumb-screw R. The other galvanometer circuit terminal T is made a part of the traveller to which the fixed spring contact is fastened.

VI. The Need for a Commutator.

When the indicator itself was over half finished the new problem of back-pressure mentioned earlier, presented itself. Consider an indicator card from a steam or gas engine. An indicator on a steam engine is used here because of the simplicity of the card. With an engine

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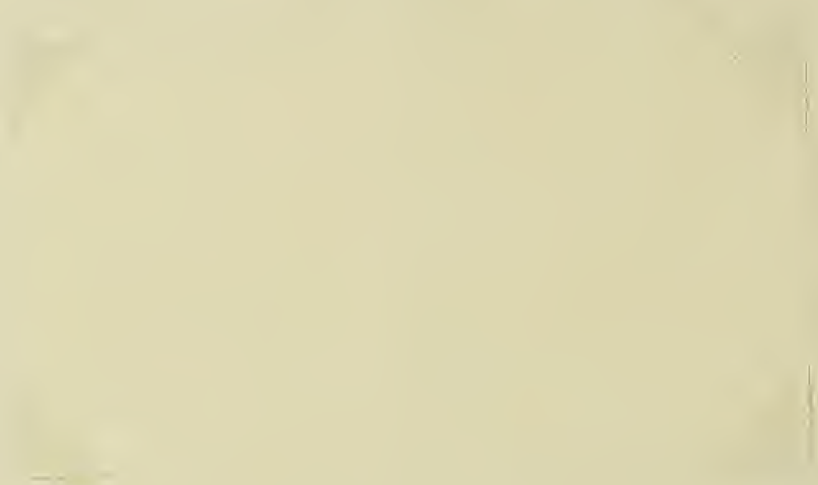

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working normally a card similar to that shown in Figure 26 will be obtained from an indicator in the cylinder. The area of the figure is a measure of the work performed by the engine, and the average height of the line is the average pressure in the cylinder over the stroke. The indicator being constructed would give a reading corresponding to the average height of the slider above the zero mark, which would be exactly what is desired. Suppose now for some

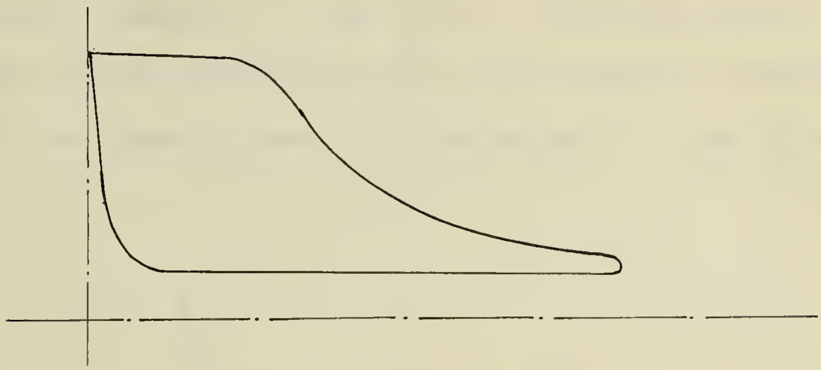

Fig. 26. Normal Steam Engine Card.

reason common to steam engines, there was something occuring in the cylinder to cause the card to take any one of the forms shown in Figure 27. In every case, the average height of the line is

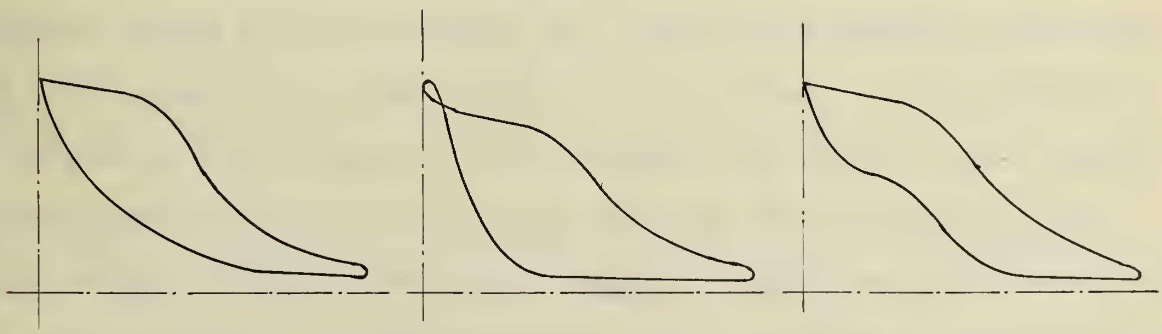

Fig. 27. Typical Defective Steam Engine Cards.

above that in Figure 26, but the increased average height results from increases in cylinder pressure on the back stroke of the piston

when the engine is doing work on the enclosed steam -- negative work. The planimeter takes cars of that part, for it is the area that is determined, and in all of these cases, the area is less. In the direct-reading indicator, however, the average height of the piston in the cylinder of the indicator is recorded and no consideration is given to the part of the cycle in which the indication is recorded. In other words, there was at that time, no arrangement in the circuit to take care of negative work. As a limiting case, for illustration, suppose a card could take the form shown in Figure 28, when the work done on the back stroke is just equal to that done on the

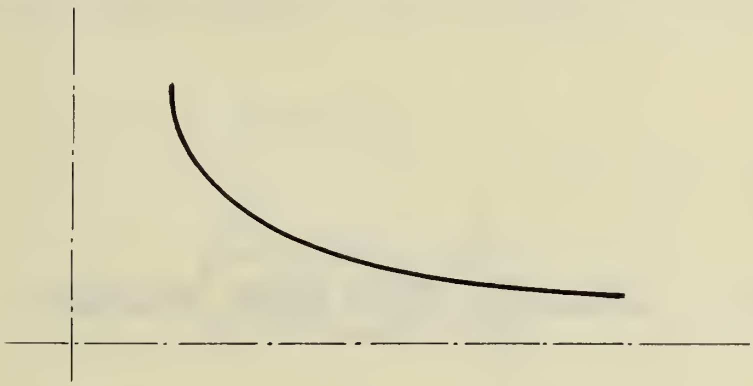

Fig. 28. Steam Card with Zero Area.

power stroke and the area, and hence the useful work, is zero. A planimeter would give zero area, but the direct-reading indicator would still read the average height of the line. The converse of this condition would appear when a condensing engine would lower the back-pressure line, increasing the area but decreasing the average height, making the direct-reading indicator give lower values.

A little thought showed that the only way such a condition could be taken care of was to change the direction of the current in the bridge every time the piston of the engine went through dead center, so that on the working stroke the readings of the galvanometer would

be positive and on the back stroke negative for any pressure developed.

Systems of electro-magnetically controlled contact points were suggested, but all had objections that made them impracticable, and a simple commutator was finally decided upon as the best solution for the problem.

The revised circuit of indicator and commutator given in Figure 29 shows that as well as two commutator segments for reversing the direction of the current, there were needed two slip-rings on the same shaft to carry the current to the commutator. Since the indicator itself would have to be grounded on the engine on which it was used, it was also essential that no part of the commutator be grounded.

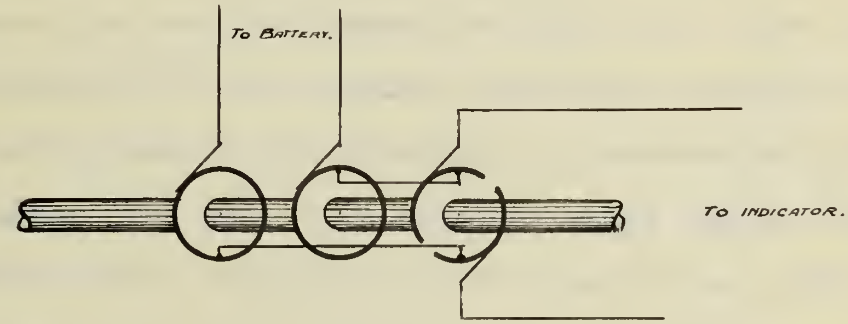

Fig. 29. Commutator Circuit.

A metal sleeve was used as the base upon which to build the rest of the commutator since that would be easier to fasten to any shaft it would be put on, and furnished a substantial support for the insulating materials and rings put outside of it. A wooden sleeve with a collar at one end was turned so that it fit snugly around the brass sleeve and extended a little over each end so that the brass could not come in contact with any near-by metal parts of the engine. Two brass rings were then cut from a piece of two-inch

tubing and turned to a close fit over the wood, and a thin fibre ring placed between them for insulation. Another ring somewhat wider was then fitted to the wood after which it was cut in two pieces directly across a diameter with as little loss of removed metal as possible, so that the distance between the ends of the segments would be very small when they were fitted around the base. Another fibre ring filled up the space between the commutator segments and the end of the wood.

After all of the pieces were fitted, they were fastened together to make the completed commutator. The brass base was grooved on its outside face so that the wires could be run from the segments to the slip-rings between it and the wood and leave room for some insulation between them and the brass, and also that there would be room to put the anchors of the segments inside and insulate them. Each slip-ring was connected electrically to a commutator segment by a wire run through the wood, the point at which the wire went through the wood into the ring serving as enough of an anchor to keep the rings from turning and nothing else but the adjacent rings and fibre pieces was used to hold them in place. With the commutator, however, more secure means had to be devised to keep the segments in place. After trying several methods it was found most satisfactory to fasten the segments by pieces of copper wire sweated into holes at the ends and bent at right angles after passing through the wooden sleeve. Thin pieces of varnished cambric tape were put between the ends of the segments for insulation. When the rings and segments were in place on the outside of the wood the brass lining was fitted to it and the whole thing filled with shellac for insulation. The shellac also served to hold the whole together to a great extent. The fibre ring on the end was rivited

to the brass lining and a set-screw put through it. It was tested for shorts and grounds at all stages of construction. The completed commutator is shown in Figure 30.

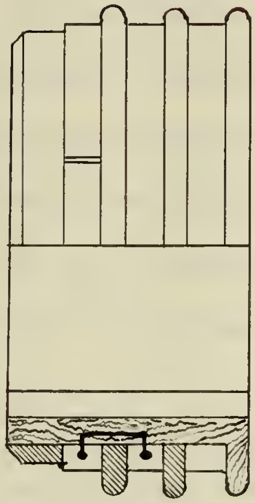

Fig. 30. Details of Commutator.

The brush-holder, shown in Figure 31 was then constructed to contain the slip-ring and commutator brushes, with a movable rocker arm so that the commutator brushes could be rotated about the center of the shaft on which the commutator was to be put. There were few

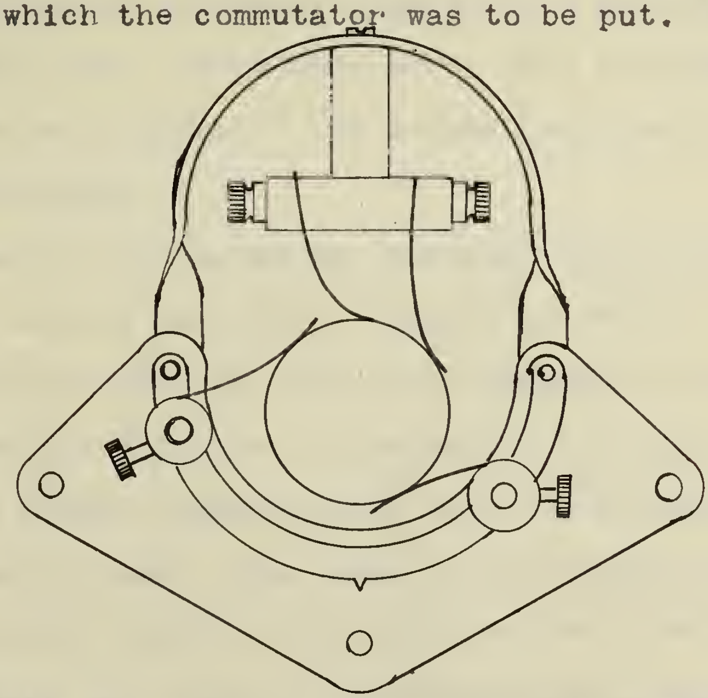

Fig. 31. Brush Holder with Rocker Arm.

conditions that placed a limit on the design of the brush-holder other than those of insulation and the fact that the commutating brushes must always be across a diameter and commutate instantly without opening or shorting the circuit.

The commutator and brush-holder were designed primarily so they would fit on a 60 horse-power Peerless engine in the Mechanical Engineering Laboratory and the distinctive shape is the result of the specialized design because of the location of available studs on the end of the crank-case to which the holder could be fastened.

VII. Calibration of the Bridge Wires.

Before the completed indicator could be used as a measuring device it was necessary to calibrate the galvanometer scale so the readings could be interpreted in terms of pressure. The electrical part of the instrument was first mounted on a Crosby Hydraulic Indicator, piston area .025 square inch, with a 20-pound spring. Figure 32 gives the diagram of the connections used for calibrating the galvanometer scale.

The force of the indicator was supplied by an ordinary oil fluid-pressure testing machine, a diagram of which is included in Figure 32. The principle of the scheme depends on the hydrostatic pressure exerted by weights on a plunger in a cylinder filled with oil which is in direct communication with the indicator piston through a series of tubes. The area of the plunger cylinder being known as well as the weight of the load on the plunger platform it is but a simple calculation to determine the pressure of the oil. This same unit pressure is then exerted on the indicator piston

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[illegible]

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and since in the commercial form of testing apparatus the weights are made to read directly in pounds per square inch, the unit pressure exerted on the indicator is at once known directly. In as much as the reading of the galvanometer is proportional to the

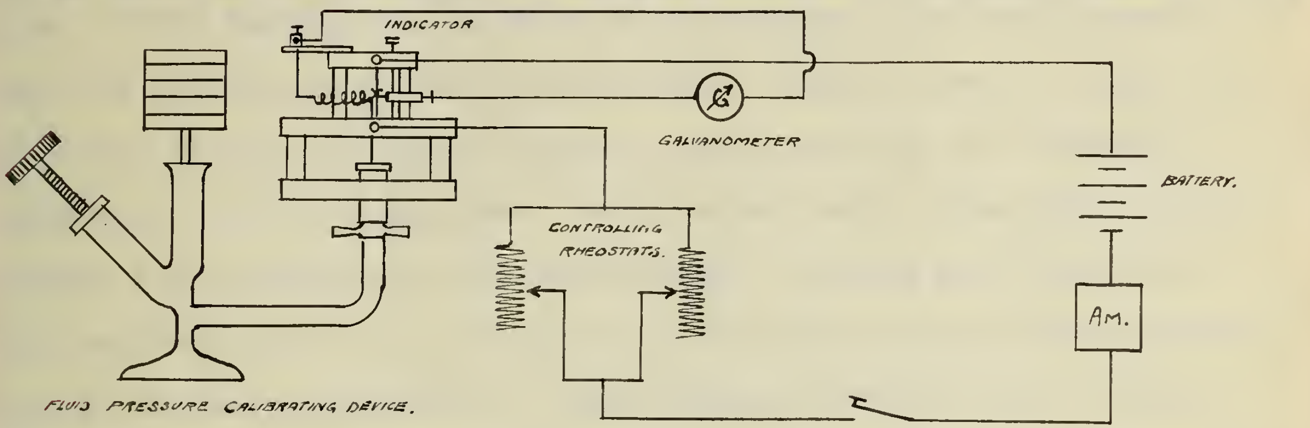

Fig. 32. Set-up for Calibration of Bridge Wires.

potential difference between the terminals, it follows that the readings of the instrument will vary with the IR drop along the bridge wire between the potentiometer circuit contacts. Pressure, however, is directly proportional to the length of deflection, following from Hooke's law, and in a wire of uniform cross-section resistance is also proportional to length. Therefore, if the galvanometer reading is to vary with pressure, the potential drop must necessarily vary with resistance only, requiring that the current in the bridge wire remain absolutely constant. An ammeter was inserted so that it would be possible to keep the current at a constant value during calibration and test. For any set of calibration data, the size of spring, piston section area, cross-section of bridge wire, and current in the bridge circuit had to be constant, for a change in any of these quantities would change the ratio of the galvanometer deflections to the unit pressure on the indicator. During any test, however, neither the indicator piston and spring,

nor the bridge wire were changed, thus necessitating that the current alone be kept constant during a run. Accordingly, in calibration data tabulations, it was necessary to record the type of indicator, the piston area, the kind of bridge wire and its cross-section, the size of the spring, the current in the bridge, the unit pressure, and the deflection of the galvanometer. Curves 1 and 2, Figure 33 give the results obtained from the first tests on the hydraulic indicator. Curve 2 was taken twenty-four hours after Curve 1 to insure the constancy of the calibration. During the time between the calibrations, the indicator and the galvanometer were subjected to the ordinary variations of room temperature and were both dismanteled and set up again to see if there was any serious variation in the calibration, due to handling or moving the instruments around. Table 3 gives the data from which the calibration curves were made.

Table 3.

Calibration Data on a 20-Pound Spring. Piston Area .025 Square Inch Manganin Bridge Wire, Cross-Section .00096 Square Inch.

Pounds per Square Inch	Curve 1	Curve 2	Bridge Wire Current
	Galvanometer Readings		
0	0	0	1.0
5	0.6	0.6	1.0
10	1.5	1.3	1.0
15	2.5	2.0	1.0
20	3.35	3.4	1.0
25	4.7	4.55	1.0
30	5.5	5.9	1.0
35	6.8	6.6	1.0
40	7.7	7.8	1.0
45	8.5	8.4	1.0
50	9.6	9.6	1.0
55	10.7	10.4	1.0
60	11.3	11.6	1.0
65	12.6	12.5	1.0
70	13.3	13.7	1.0
75	14.6	14.5	1.0
80	15.5	15.8	1.0
85	16.7		

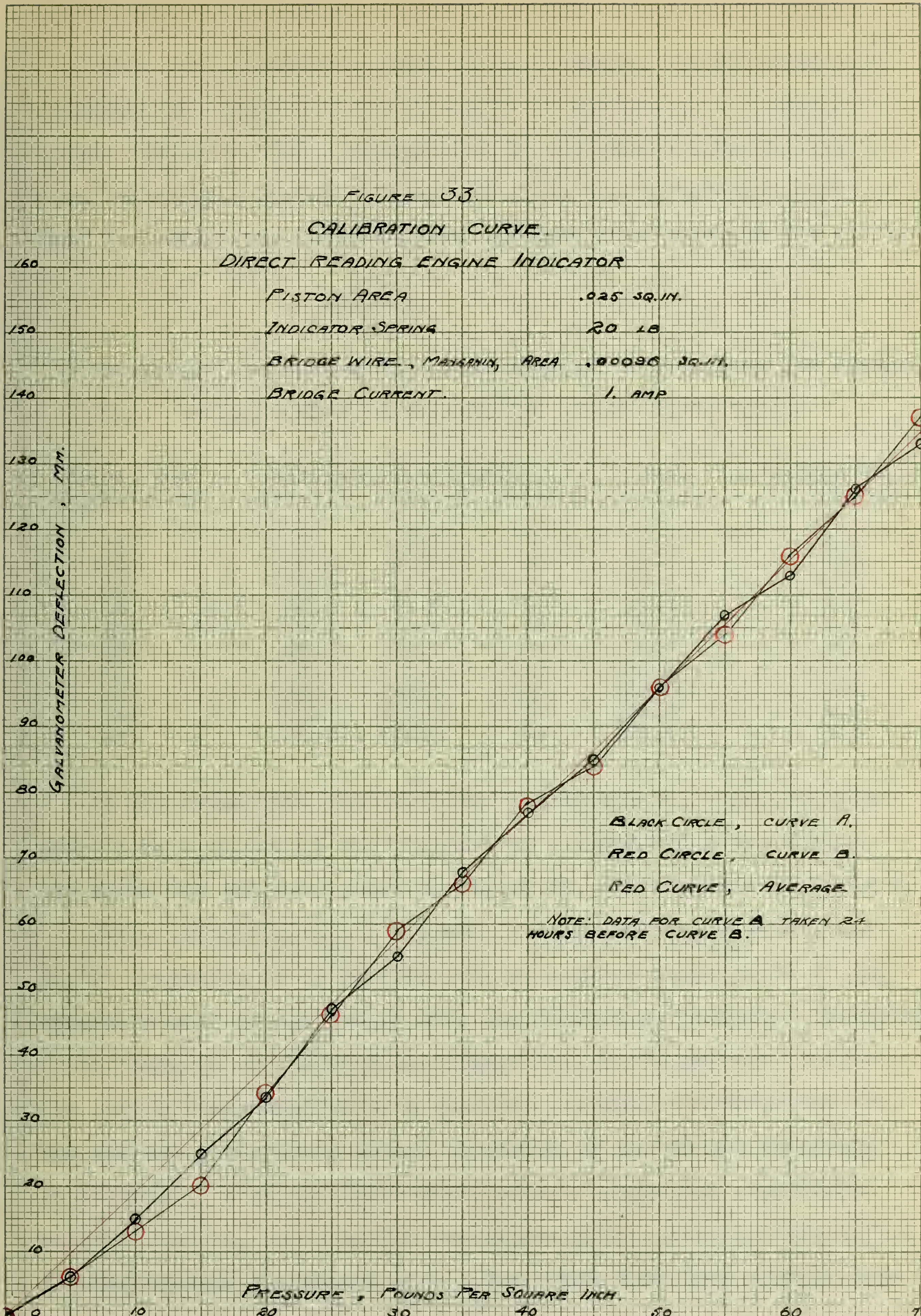
FIGURE 33.
CALIBRATION CURVE.
DIRECT READING ENGINE INDICATOR
PISTON AREA .025 SQ.IN.
INDICATOR SPRING 20 LB
BRIDGE WIRE, MANGANIN, AREA .00036 SQ.IN.
BRIDGE CURRENT. 1. AMP
BLACK CIRCLE, CURVE A.
RED CIRCLE, CURVE B.
RED CURVE, AVERAGE.
NOTE: DATA FOR CURVE A TAKEN 24 HOURS BEFORE CURVE B.
GALVANOMETER DEFLECTION, MM.
PRESSURE, POUNDS PER SQUARE INCH.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

Later for purposes involved in other tests, the potentiometer equipment was removed from the hydraulic and put on a Crosby gas-engine indicator with a piston area of .25 square inch and a 100-pound gas-engine spring. Figure 34 shows the calibration curve of this instrument and Table 4 gives the data from which it was plotted.

Table 4.

Calibration Data on a 100-Pound Spring. Piston Area .25 Square Inch. Manganin Wire, Cross-Section .00096 Square Inch.

Pounds per Square Inch.	Galvanometer Readings. Trial 1	Trial 2	Trial 3	Mean Reading	Bridge Wire Current
0	0	2.0	0	0.7	1.0
5	20.0	22.5	23	21.8	1.0
10	39.0	41.0	41	40.3	1.0
15	59.5	61.0	61	60.5	1.0
20	78.0	79.0	78	78.3	1.0
25	95.0	98.0	97	96.7	1.0
30	113.2	115.0	115	114.3	1.0
35	132.0	133.0	134	133.0	1.0
40	155.5	153.0	152	153.5	1.0
45	177.0	174.0	173	174.7	1.0

It was found that the 100-pound spring was too light for the gas-engine work and it was replaced by a 160-pound steam spring, the curve for which is given in Figure 35, and the data in Table 5.

Before entering into a discussion of the actual engine tests of the indicator it is well to take up a brief description of the apparatus used in connection with the electrical circuits. Referring to the diagram of connections, Figure 36, in the primary circuit the current was supplied by a six-volt automobile storage battery. The current controlling device consisted of two 25-ohm rheostats in multiple. A single-throw knife switch opened and closed the primary circuit, and a Weston one-ampere meter measured the current flowing through the bridge wire. The leads from this circuit were

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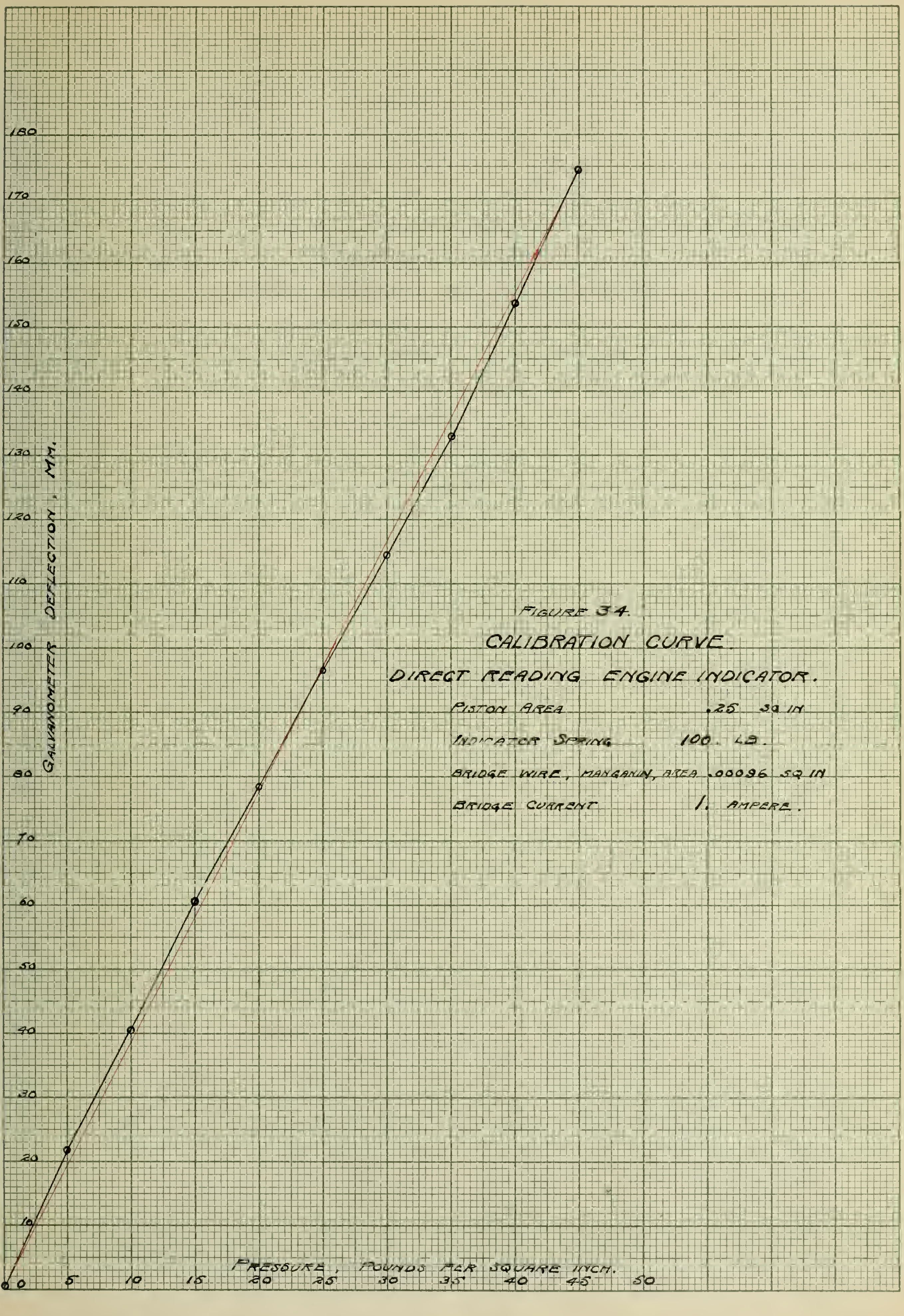

FIGURE 34.

CALIBRATION CURVE.

DIRECT READING ENGINE INDICATOR.

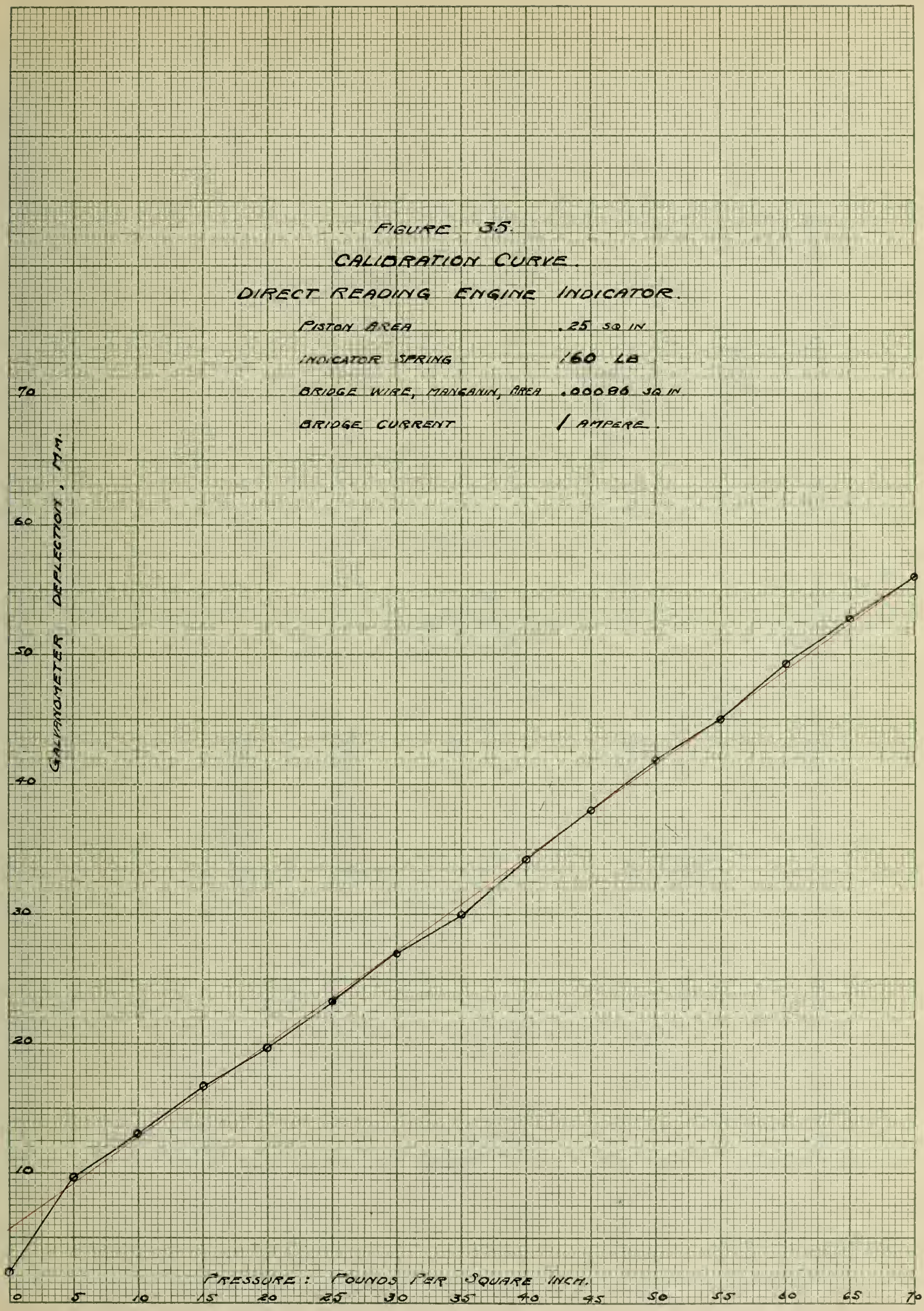
FIGURE 35.
CALIBRATION CURVE.
DIRECT READING ENGINE INDICATOR.
PISTON AREA .25 SQ IN
INDICATOR SPRING 160 LB
BRIDGE WIRE, MANGANIN, AREA .00086 SQ IN
BRIDGE CURRENT 1 AMPERE.
GALVANOMETER DEFLECTION, MM.
70
60
50
40
30
20
10
PRESSURE: POUNDS PER SQUARE INCH.
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70

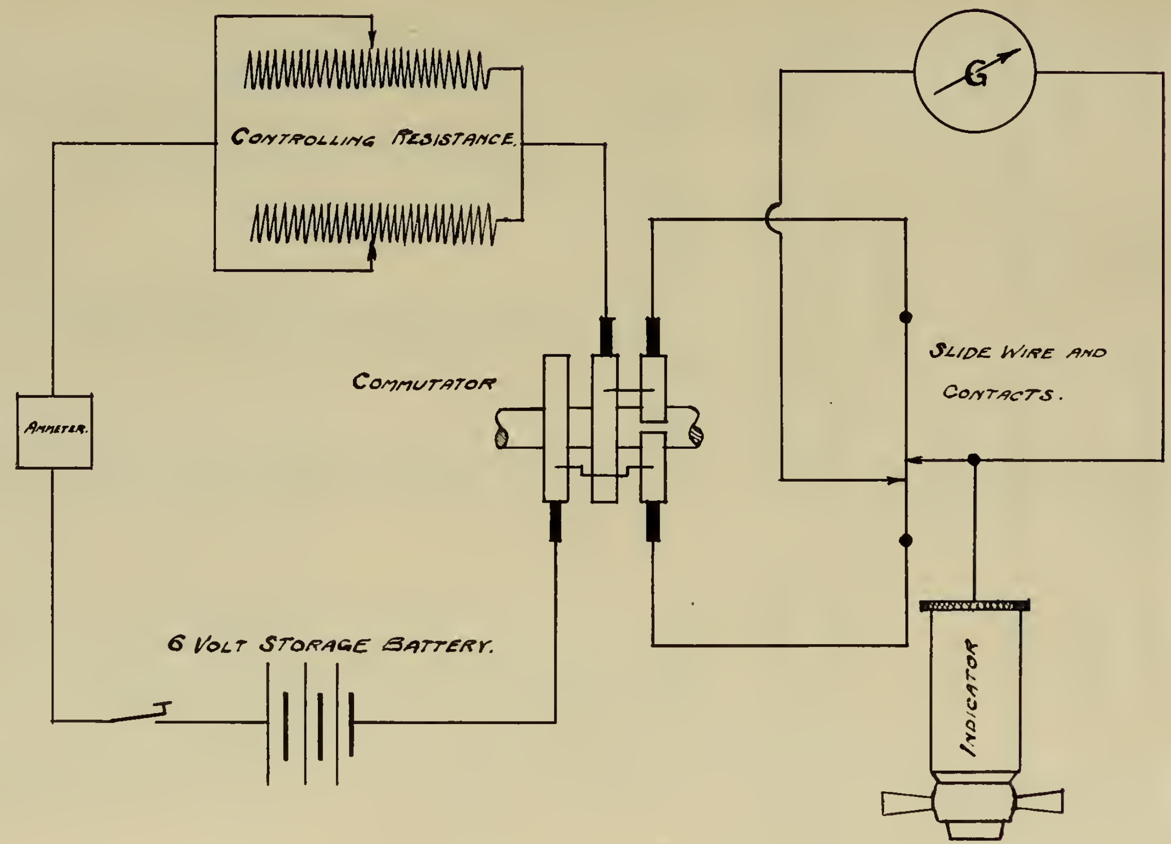

DIAGRAM OF CONNECTIONS FOR DIRECT READING PRESSURE INDICATOR.

FIGURE 36.

connected to the slip-ring brushes which were internally connected to the commutator segments on the same shaft. The current was taken off of the commutator by two other brushes and led to the manganin bridge wire which completed the primary circuit. The commutator had to be placed on the crank-shaft of the engine, as explained before, so that the direction of the current would change at the dead center of the piston travel and also to have the reversals in synchronism with the piston speed. The galvanometer circuit was very simple

Table 5.

Calibration Data on a 160-Pound Spring. Piston Area .25 Square Inch. Manganin Bridge Wire Cross-Section .00096 Square Inch.

Pounds per Square Inch.	Galvanometer Readings. Trial 1	Trial 2	Trial 3	Mean Reading	Bridge Wire Current
0	0	4	4	2.7	1.0
5	8	10	11	9.7	1.0
10	12	13	14	13.0	1.0
15	16	17	17	16.7	1.0
20	19	20	20	19.7	1.0
25	24	23	23	23.3	1.0
30	27	27	27	27.0	1.0
35	30	30	30	30.0	1.0
40	35	34	34	34.3	1.0
45	38	38	38	38.0	1.0
50	42	42	42	42.0	1.0
55	45	45	45	45.0	1.0
60	49	50	49	49.3	1.0
65	53	53	52	52.7	1.0
70	56	56	56	56.0	1.0
75	60	60	61	60.3	1.0
80	66	65	65	65.3	1.0

and consisted of a Leeds and Northrup portable D'Arsonval galvanometer connected to the potentiometer circuit terminals on the indicator. Figure 37 shows the apparatus set up for test on the 60 horse-power Peerless automobile engine.

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VIII. Tests on the Peerless Engine.

As soon as the commutator and indicator were finished they were put on the Peerless engine in the Mechanical Engineering Laboratory and a series of tests was run with them there. The commutator was adjusted so that the current in the bridge was reversed just as the engine went through dead center, and this adjustment was checked after each test. The engine runs at about 1800 revolutions per minute and is capable of developing up to 60 horse-power. Since it was obviously impossible to check the readings of indicated horse-power given by the direct-reading indicator against diagrams from a card indicator because of the speed, the brake horse-power was determined and the indicated horse-power calculated from that and the efficiency of the engine.

When the galvanometer was at zero and the bridge wire current was fixed at one ampere, the engine was started. The galvanometer did not give much of a reading when the engine was running light,

Fig. 37. Indicator and Apparatus on Peerless Engine.

but since the vibrations of the engine at that load were very

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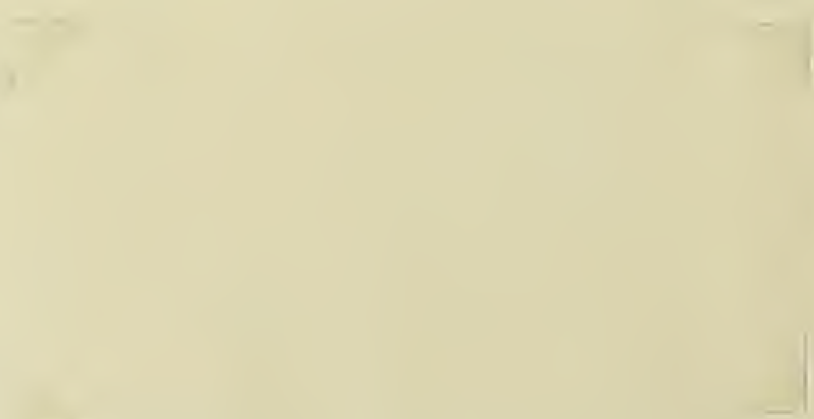

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severe, the blame was put there and the load put on. The load was increased gradually up to about fifty horse-power, but the readings of the galvanometer did not follow the increases in pressure as they should have. The readings did not increase with the load, nor even stay constant for any given load, and were at no time within fifty per cent of what they should have been.

In seeking a cause for these low readings, the entire indicator circuit was checked over and resistance measurements of the commutator taken both at rest and running. No trouble was found in the circuit and the only other source of error was in the indicator itself. It was finally decided that because of the extremely high frequency of the explosions, the time element was too short to allow the spring accurately to follow the variations in pressure without a time lag.

From the appearance of the operation at speeds greater than 1000 revolutions per minute, it seemed that the piston never reached the maximum pressure nor went down to the minimum but vibrated somewhere between them. It was thought desirable to use a larger piston area and a stronger spring which would have the ability to damp out vibrations due to the inertia effects of the spring and attached parts. In the weak spring which had been used with the hydraulic instrument, the natural period was comparatively low and was perhaps in the neighborhood of the frequency corresponding to the rate of rise in pressure following an explosion in the cylinder. When the change had been made to another indicator another series of tests was made on the Peerless engine but with little better results than before. The readings of the galvanometer followed the variations in pressure better, but they were still far below the pressure they should have indicated.

It seemed quite possible that even the stronger spring was unable to act quickly enough to follow the rapidly varying pressures under it. It was obviously useless to make further tests on a machine that ran at such high speeds because the two tests here recorded showed conclusively that the machine would not work at such speeds as it was then constructed. Another type of indicator, mentioned later, in which the piston and spring were to be replaced by a diaphragm, suggested itself, but there was no time in which to start an entirely new indicator. For that reason it was decided to apply the indicator to a slower speed gas engine and observe the results there.

IX. Tests on an Otto Engine.

Another gasoline engine in the Mechanical Engineering Laboratory, a 300-r.p.m., 10 horse-power Otto engine was available at this time so the instruments were moved over to it. The commutator was taken off of the crank-shaft of the Peerless engine and fitted to a solid steel cylinder that could be screwed into the shaft of the Otto engine. The brush-holder was mounted on the end of an iron rod that was supported in a heavy iron base which could be moved around independently of the engine. Figure 38 shows the brush-holder and commutator in place on the engine. The indicator was placed on a cock already on the engine as shown in Figure 39.

There were two ways of checking the results to be obtained from this engine. First there was a Prony brake from which readings of brake horse-power could be determined, and second there was the opportunity to put a card indicator on the engine and check directly

the mean effective pressure developed. Both methods were tried.

After everything was adjusted to the new engine, it was started and a series of runs made as had been done on the Peerless engine.

Fig. 38. Commutator and Brush Holder on Otto Engine.

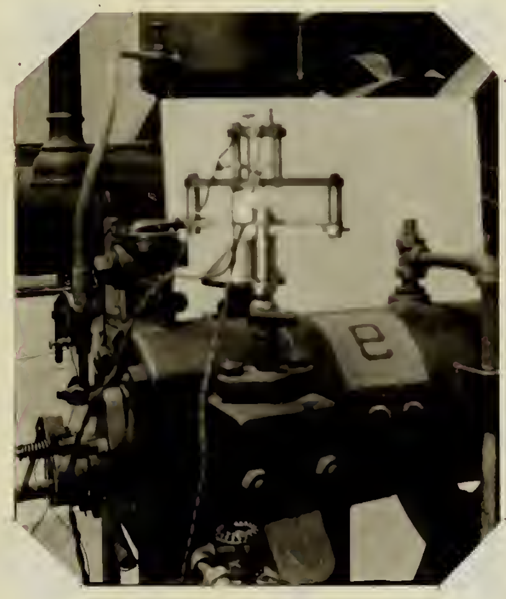

Fig. 39. Indicator on Otto Engine.

Table 6 gives the results that were obtained from the tests. Here it is seen that the indicator recorded pressure that gave indicated horse-power in excess of the actual horse-power developed by the brake. The friction horse-power of the engine, however, figured

from the indicator readings, did not remain at all constant as they should have and an investigation was begun to find the source of error. On taking the indicator apart it was found that the spring had been badly smashed up because it was too weak. Accordingly, a heavier, 160-pound spring, was inserted in the instrument and another test run with results tabulated in Table 7. In addition, a number of

Table 6.

Indicated Horse-Power Test of Otto Engine. 100-Pound Spring.

Gross Weight.	Force	Galvanometer	Pressure	I.H.P.	B.H.P.	Mech. Eff.
40	16.5	72	18.5	9.10	4.95	54.4
45	21.5	78	20.0	9.84	6.45	65.6
50	26.5	84	21.5	10.58	7.95	75.2
55	31.5	93	23.8	11.76	9.45	80.4

Speed 300 r.p.m. Tare on scales 23.5 pounds. Brake arm 63 inches. Bridge wire current one ampere.
Bore 5.75 inches. Stroke 12.5 inches.

Table 7.

Indicated Horse-Power Test of Otto Engine. 160-Pound Spring.

Gross Weight.	Force	Galvanometer	Pressure	I.H.P. Dir. Rd.	B.H.P.	I.H.P. Cards.	Mech. Eff.
40	....	....	....	...	...	11.75	....
45	22	22	24	11.80	6.6		56.0
50	27	24	26	13.04	8.1	12.58	61.8
55	32	25	28	13.78	9.6		69.5
60	37	29	33	16.24	11.1		68.5
65	42	32	38	18.70	12.6		67.5

Speed 300 r.p.m. Tare 23 pounds Brake arm 63 inches.
Bridge wire current one ampere Spring 160 pounds.

gas engine indicator cards, types of which are presented in Figures

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[illegible]

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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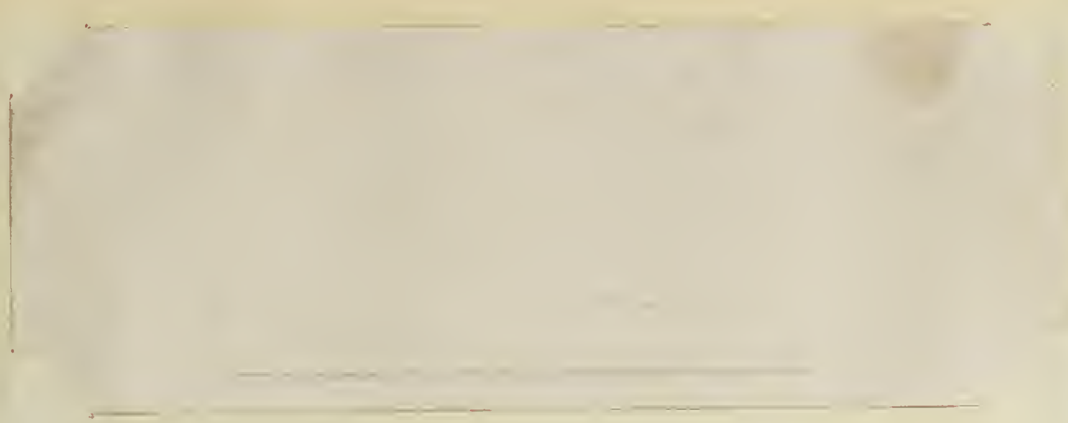

Fig. 40. Gas Engine Card. Light Load, Rather Smooth.

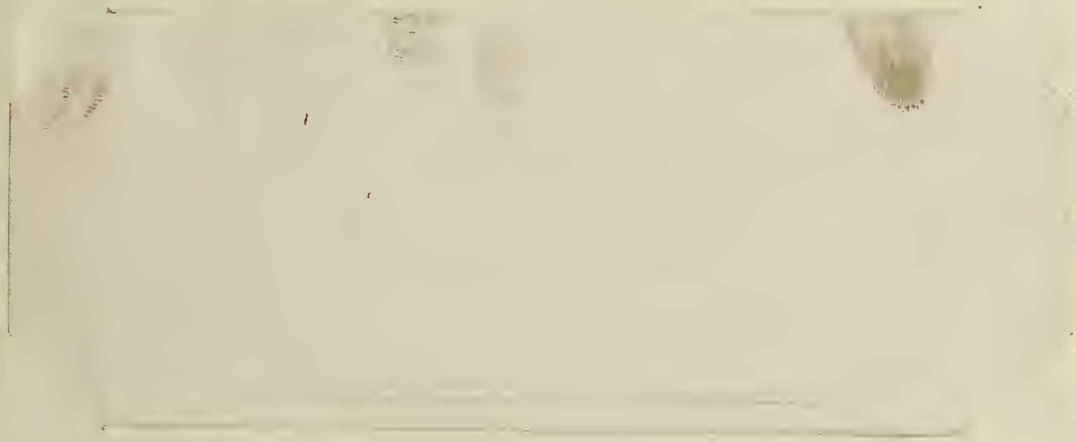

Fig. 41. Gas Engine Card. Heavier Load, Slightly Rough.

Fig. 42. Heavy Load. Marked Inertia Effects.

50

Fig. 43. Very Heavy Load. Card Almost Useless.

40, 41, 42, and 43, were taken at different loads and the indicated horse-power calculated from them. These results are also given in Table 7. It is interesting to note that the indicated horse-power calculated from the direct-reading indicator is in each case greater than the horse-power figured from the card, mean effective pressures showing perhaps that the electrical instrument is more sensitive than the standard mechanical apparatus.

In order to determine the instantaneous behavior of the indicator an oscillograph was inserted in the electrical circuit instead of the galvanometer and the commutator was taken out so that a record of the wave of the current fluctuation corresponding to the pressure variation in the cylinder was obtained. In previous tests where the normal bridge wire current was one ampere, the current through the galvanometer would not have affected the oscillograph, but now the current was run up to 15 amperes momentarily while the oscillogram was being taken.

Figure 44 was the first picture taken, with a bridge wire current of five amperes, and a load of about five horse-power on the brake. The general shape of the diagram shows up clearly, but the deflection is too small to show up any defects that might be in the cycle. As a matter of explanation, it might be well to note that the printer made the pictures the reverse of the way one is accustomed to look at an indicator card. The next picture taken is shown in Figure 45. It was taken with about ten amperes in the bridge wire and gives a size of diagram in which the path shows up better. The line is not smooth as it appeared to be in the first one, but shows marked irregularities, especially after the explosion. Figure 46 shows the next picture taken with about thirteen amperes in the bridge

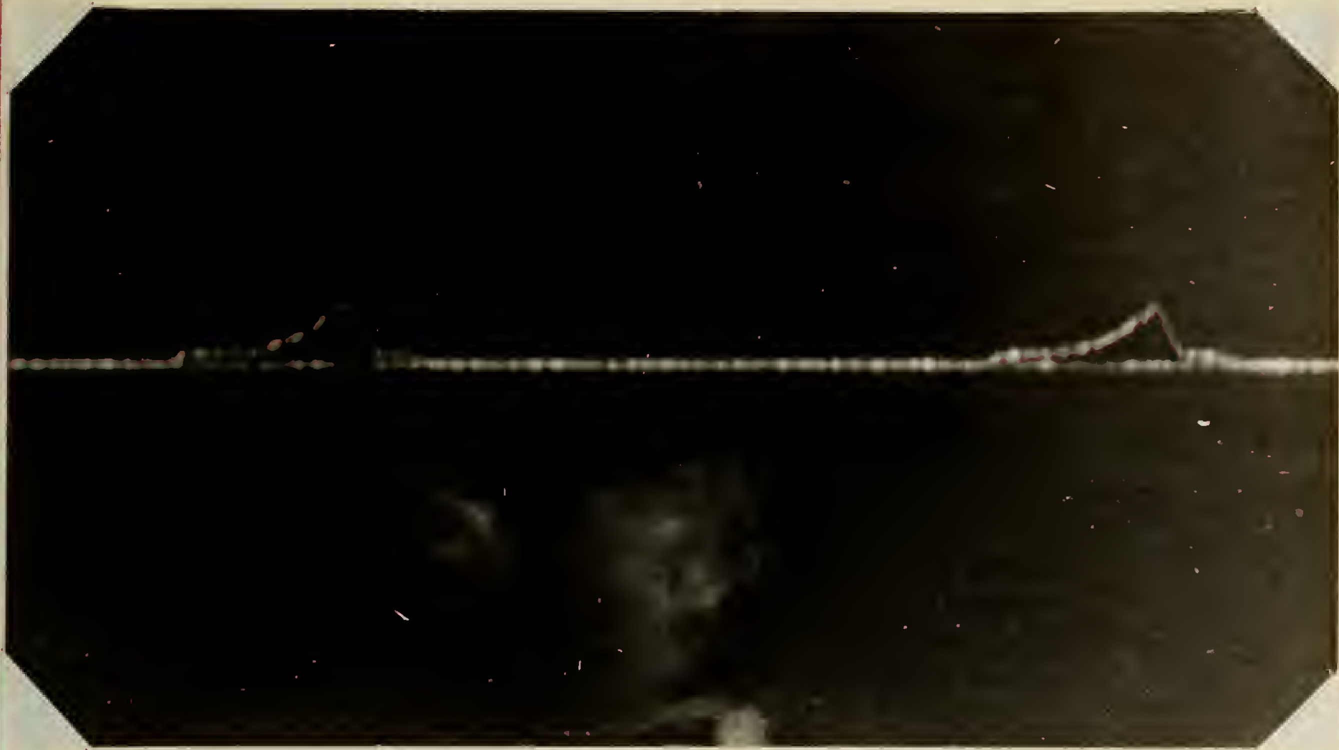

Fig. 44. Pressure-Time Diagram of Cylinder. Five Amperes.

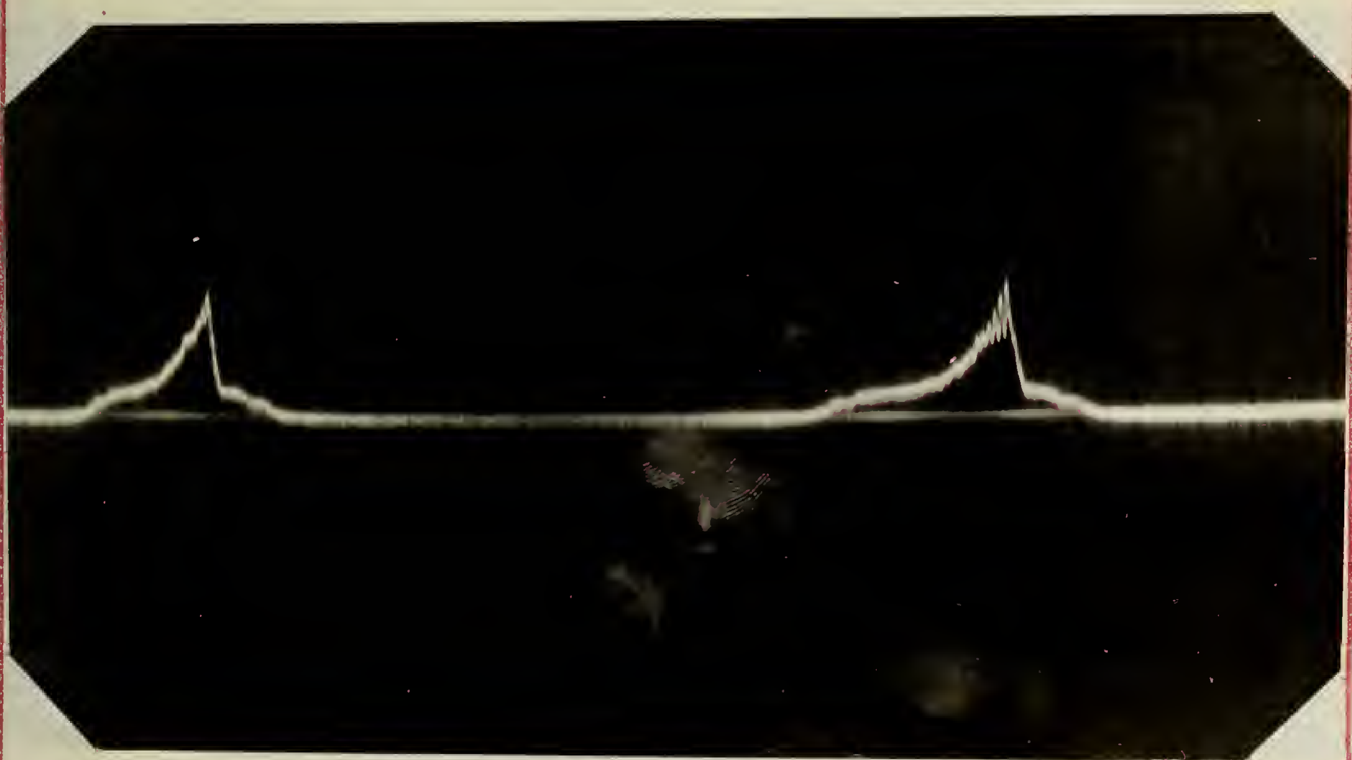

Fig. 45 Pressure-Time Diagram. Ten Amperes in Bridge.

wire. The diagrams are correspondingly larger and the irregularities show up even plainer than before. Figure 47 shows a record of the pressure as the engine passed through a single cycle. All of the events in the cycle are clearly visible, and the path is unbroken, showing that the contact was following the pressures and staying on the bridge wire at all times. The current in the bridge for this picture was fifteen amperes and the brake load about ten horse-power. The irregularities at the begining of the expansion are very plainly marked here, and will be discussed later.

The commutator was next examined for defects that would show up only in the oscillograph. Figure 48 shows a picture taken when the normal current of one ampere was flowing through it. There are some irregularities in this path also, and they will be discussed later but the path shows that the commutator was reversing the current almost instantaneously without a noticable open or short circuit.

X. Conclusions.

Sliding Contact.

During the early stages of the development, it was thought the variable contact resistance and the thermo-couples between metals sliding over each other would be the causes of the greatest difficulties to overcome. The selection of a steel-spring contact working over a manganin wire have practically eliminated these troubles, for in all of the tests, especially those in which the oscillograms were made of the contact in actual operation on the engine, the results seem to prove that the contact was staying fast on the bridge wire. On none of the indicator oscillograms does the current come back to

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

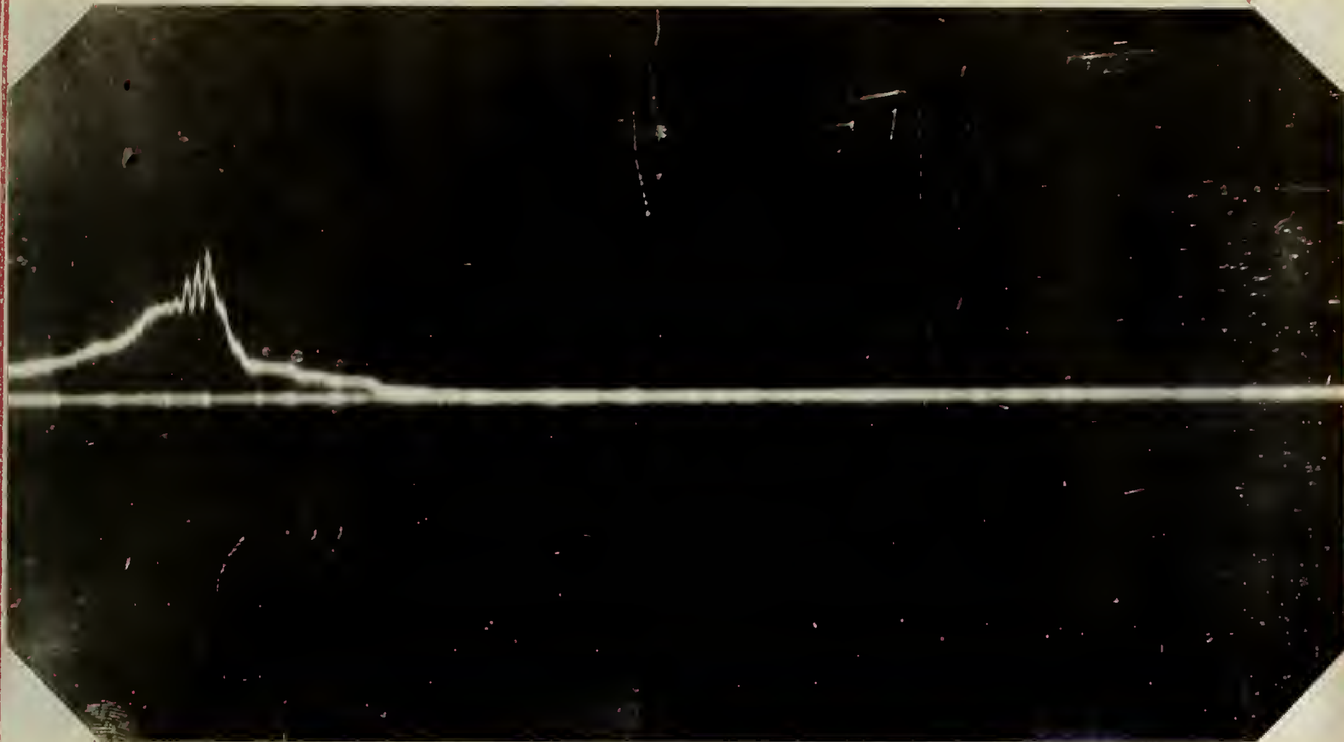

Fig. 46. Pressure-Time Diagram. Thirteen Amperes.

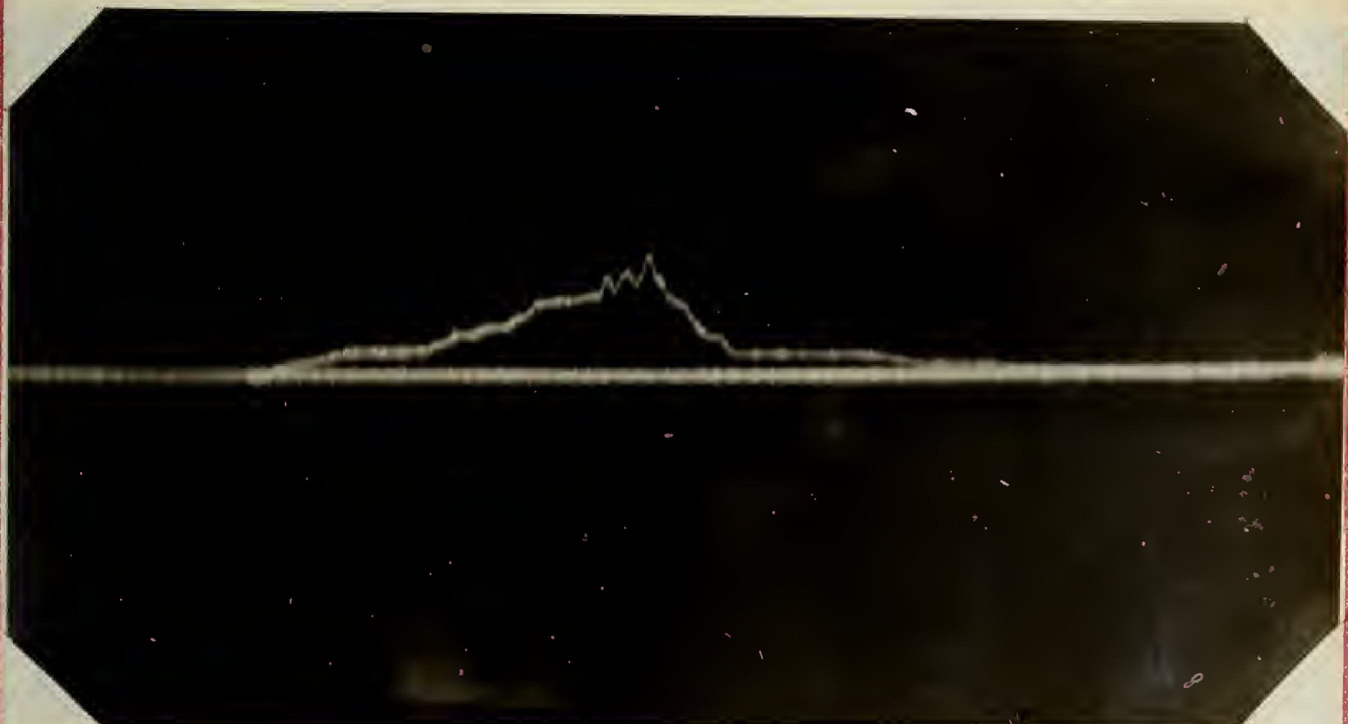

Fig. 47. Pressure-Time Diagram. Fifteen Amperes.

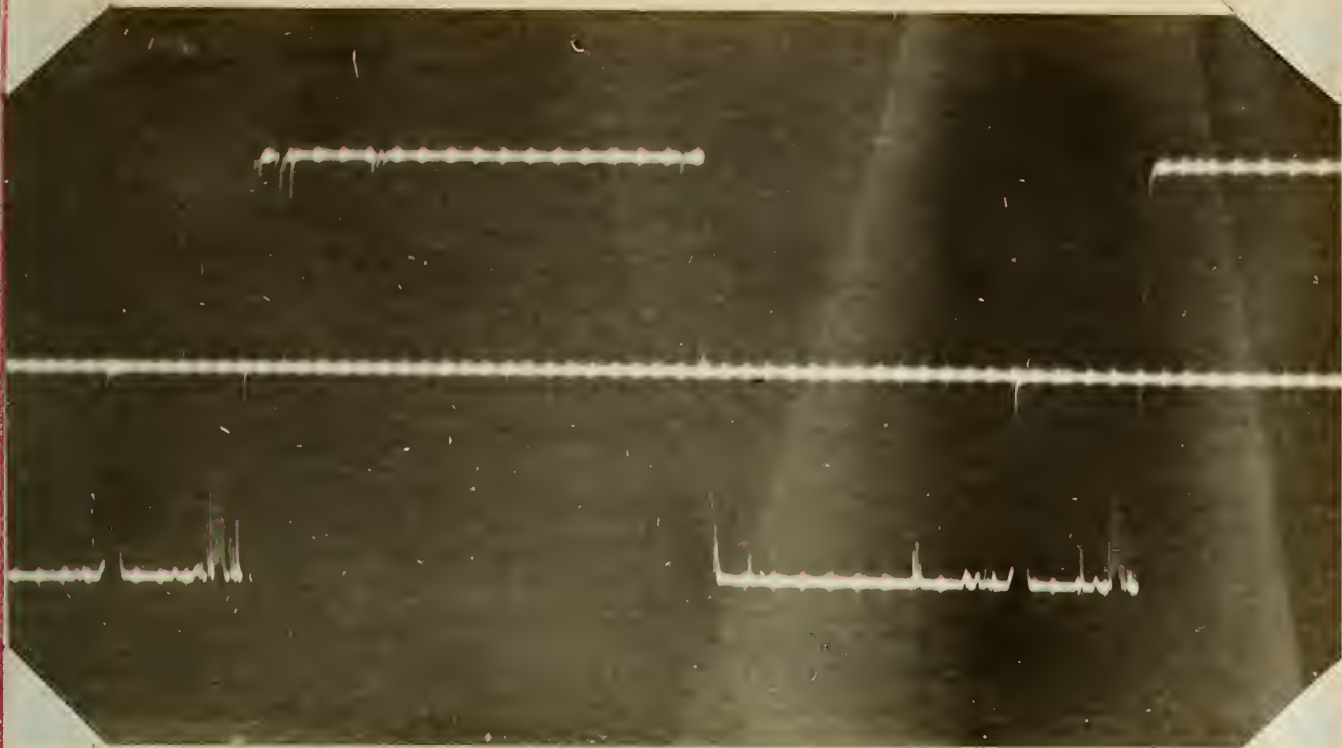

Fig. 48. Commutator Current. One Ampere Flowing.

Fig. 49. Commutator Current, Calibrated. One Ampere through Commutator, One Ampere through Bridge Wire.

zero nor are there any wavy fluctuations in the record other than those due to the pressure changes. Further evidence that thermocouples do not impair the accuracy of the instrument is supplied by the fact that after tests in which the indicator became heated to at least sixty degrees above room temperature, the galvanometer always returned to its original zero reading at atmospheric pressure.

Spring Inertia.

Another difficulty did present itself, however, which was not looked for at the begining of the investigation. It was evident from the tests on the high-speed engine that there was an inherent time lag due to internal spring inertia which on speeds of over 600 or 700 revolutions per minute rendered any device involving an indicator spring, useless. It was found that the working period of stiff springs was greater than the frequency at which the weaker springs would operate. In short, under high speeds, the changes in pressure came so rapidly that the spring did not have time to take up the instantaneous positions corresponding to the rapidly changing forces acting on it. There seems to be a possibility that an indicator using a diaphragm instead of a spring might be developed to increase the speed range of the instrument.

Back-Pressure Adjustment.

Though the suggestion came too late to be tried experimentally it is now thought that the use of a back-pressure adjustment in the indicator had passed away with the adoption of the commutator to subtract out negative work. It seems that the permanently fixed terminal of the potentiometer circuit on the indicator can be at any point on the bridge wire without affecting the reading. The reason

is evident if the two waves shown in Figure 50 are considered, the

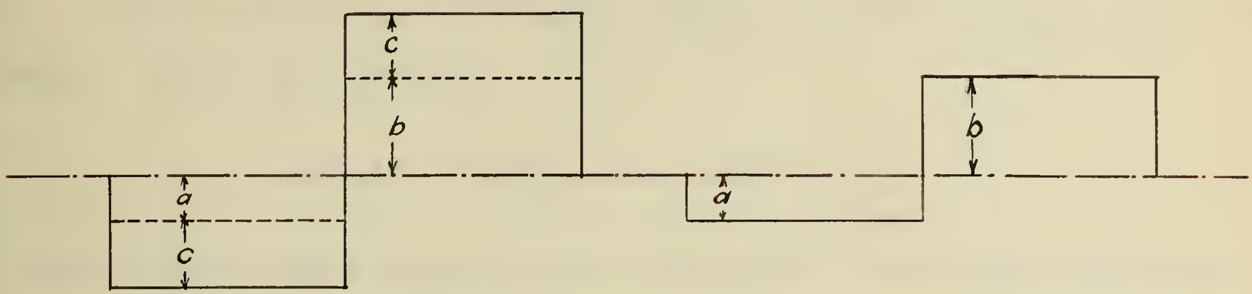

Fig. 50. The Function of the Back-Pressure Adjustment.

average values of which are obviously equal. This same reasoning will apply to the wave drawn by the indicator. The back-pressure adjustment simply shifts the zero axis, and since it shifts it the same amount on the positive stroke that it does on the negative stroke, the net result has no effect on the reading.

The Reading of the Indicator.

Let it be here understood that the indicator does not read mean effective pressure, which when multiplied by cycles per minute, length of stroke, and area of piston gives the indicated horse-power. It reads the average working pressure over the entire stroke or length of piston travel, so that to compute indicated horse-power the following considerations must be observed:

$$\text{I.H.P.} = \frac{\text{PLAN}}{33{,}000} \qquad \text{where,} \qquad (8)$$

P is the galvanometer reading in pounds per square inch,

L is <u>twice</u> the length of stroke in feet,

A is the area of the piston in square inches, and

N is the revolutions per minute.

[illegible]

This formula holds for gas engines, steam engines, or anything, regardless of the cycles per minute, working strokes, or anything else. These factors are all taken care of in the averaging performance of the galvanometer.

Inertia of Mechanical Indicators.

Some authors have assigned the reason for the jaggy appearance of the gas-engine card to the inertia of the mechanical multiplying devices on the indicator. In as much as these same oscillations are present on the photographic records of the electrical indicator, where no multiplying devices are used, it seems plausible that the vibrations are due to the natural vibrations of the spring or perhaps* to a " series of explosion waves, correctly recorded by the indicator."

Finally, let a word be said about some possible errors which might arise in the use of the instrument. It is first, important that the current drawn by the galvanometer be exceedingly small compared to the bridge wire current, otherwise the current will not be equal in all parts of the bridge wire the the IR drop will not be proportional to the length. Second, the commutator must be adjusted so that the current is reversed just on dead center of the piston travel, and must commutate at each end of the stroke. Third., the commutator must be kept clean so that the resistance will not change the current in the bridge wire, which must remain absolutely constant. Every spring has a different calibration on the galvanometer, as does every bridge wire. And in conclusion, the galvanometer must have a permanent field,--not dynamometer type.

* Carpenter and Diedrichs, p. 685.